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ICE STRENGTH INDEXER

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by

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17. Abstract

Ice tank simulation of ice breaking ships is clearly very dependent on the mechanical properties of the simulated ice. The conventional methods used to measure the mechanical properties of the simulated ice are time consuming and restricted to only one or two of the strength parameters.

This report documents the ongoing development of a device, known as the Ice Strength Indexer, which measures the flexural, shear and compressive strength of the ice continuously along the entire length of the ice tank. The report is divided into two sections, the first part describes the latest development of the Indexer design, model tests and calibration of strength values to those measured using the conventional methods. The second part describes a method to apply the output from the Indexer to correct the model resistance for variations in ice strength along the length of the tank.

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17. Résumé

Les essais sur modèle réduits de cargo brise-glace reposent de toute évidence sur la connaissance des caractéristiques mécaniques de la glace modèle. Les méthodes classiques mises en oeuvre pour déterminer celles-ci sont laborieuses et ne s'appliquent qu'à un ou deux des paramètres de résistance.

Le présent rapport fait état de la mise au point d'un dispositif appelé Indexer qui permet de mesurer en continu la résistance à la rupture en flexion, à l'écrasement et au cisaillement d'une glace modèle, d'un bout à l'autre du bassin. Ce rapport, qui comprend deux parties, décrit d'abord les plus récentes modifications apportées au dispositif, donne les résultats d'essais sur des glaces modèles et établit la corrélation entre les valeurs enregistrées par l'Indexer et celles mesurées selon les méthodes classiques. En deuxième partie, il expose une méthode permettant d'utiliser les résultats obtenus avec l'Indexer pour corriger les variations de résistance de la glace dans l'axe longitudinal du bassin.

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SUMMARY

1. Introduction

The Indexer was developed by Melville, in association with the National Research Council's (NRC) Hydraulics Laboratory and the Institute for Marine Dynamics (IMD), to measure the properties of model ice and incorporate them in the calculation of icebreaking resistance. The initial development of the Indexer was undertaken at the Hydraulics ice tank of the NRC in Ottawa in association with Dr. Timco and sponsored by the Transportation Development Centre (TDC). The results from this work demonstrated that the concept of using the Indexer to calibrate the strength of an ice sheet worked very well and that the Indexer could become a useful and time saving tool for the IMD ice tank.

This report describes the work undertaken to refine the Indexer instrumentation and develop a procedure to incorporate the measured ice strength into the total prediction of an icebreakers performance.

2. Indexer Design Optimisation

Following the completion of the initial design and model testing of the Indexer at the NRC Hydraulics Laboratory in Ottawa, the Indexer was shipped to St. John's and a series of ice sheets were used to investigate the capability of the Indexer in the IMD tank. These tests resulted in a number of design modifications, which were then undertaken by the original fabricator of the Indexer in Ottawa.

Nine ice sheets have been tested at IMD with the Indexer. All of these tests were made on an opportunity basis after the completion of other dedicated model tests. During each test the load cell output signals from the Indexer's bending, shear and crushing plates, and the speed of the towing carriage, were recorded digitally for subsequent analysis. The data were recorded at a sampling rate of 50 HZ for each channel. The test data which have been compiled includes various ice thickness and strength conditions ranging from 3 cm to 6 cm in thickness and from 15 to 100 kPa in flexural strength.

Four outputs were recorded; the manually measured ice strength, the derived strength from the Indexer, the Indexer force output, and the manually measured ice thickness. The data was recorded as a function of position in the tank. The trend of ice strength calculated by the Indexer appears to correlate quite well with the manual ice strength record. The absolute values of the two strengths are different and reflect the measuring and calculation procedure used by each method.

There have been two major findings from this work that may significantly affect the capability of an ice tank to fulfill its objective of simulating a uniform, consistent ice sheet.

- A number of the ice sheets tested showed significant variations in the crushing, shear and flexural strength.

- The conventional tests do not fully define the strength variation.

Although the variation of ice strength will, to some degree influence all bow forms, the extent to which these variations will influence the resistance of a particular model and, therefore, the prediction of the full scale performance of a ship, will depend on the type of bow and the mode with which it breaks the ice. However, since a conventional bow will break ice in a combination of bending, crushing and shearing, it can be anticipated that all model tests may be effected in some way.

3. Development of Full Scale Prediction Technique

The objective of this element of the project was to assess, through a theoretical approach, the effects of the ice strength on the level ice resistance obtained from model scale experiments. This may then be used to develop a practical correction procedure to compensate the measured model resistance for variations in the ice strength and thereby produce more accurate full scale resistance predictions.

Generally, the resistance to a ship operating in the continuous level icebreaking mode can be divided into the following components:

- icebreaking,
- ice submersion, and
- velocity.

Experiments at full scale together with model scale resistance tests, have shown that the 'icebreaking' component of resistance is strongly affected by the strength of the ice. However, due to the different icebreaking mechanisms that will occur for different bow shapes, any variation of ice strength from target values may affect hull forms differently.

To ensure that the correct modifications are made to resistance for variations in model ice strength it is necessary to evaluate the preponderance of each type of bow form to break ice in flexure, shear and crushing. The most appropriate method to evaluate these values is to develop a mathematical expression that attributes a specific relationship between resistance and ice strength for a range of bow forms. The approach adopted was to define these relationships based on our present understanding of ship/ice interaction mechanisms.

The development of the expressions and description of the formulations have been divided into three parts:

- analysis of ice breaking mechanisms,
- development of hull form coefficients, and
- application of the analysis to the full scale performance prediction.

A computer model, developed to simulate the icebreaking process, is used to derive the icebreaking forces and hull form coefficients. An example of hull form coefficients has been developed for three icebreaker hull forms, the original ARCTIC, built in 1978, the modified ARCTIC, fitted with a Melville bow in 1986, and an R-Class hull form.

The resultant analysis shows that the icebreaking action of each bow is different. Based on the crushing coefficients the old Arctic bow is less efficient in icebreaking than the Melville bow or the R-Class bow. The bending coefficients show that the ice will be broken, predominantly by bending, by all three bows. The shear failure mode was not found to be a primary icebreaking mode for the three bows within the range of the ice conditions being investigated.

An analysis of the computer program results has shown that, within the range of the ice conditions being investigated, the dependence of the icebreaking force, or resistance, on the ice flexural and compressive strengths can be represented reasonably well with the following expression:

$$R \sim (\sigma_f)^A \left(\frac{\sigma_c}{\sigma_f}\right)^B$$

The exponent of each factor is found to vary with hull form as well as ice thickness. Index 'A' is the exponent of the flexural strength in the icebreaking resistance expression when the compressive strength to flexural strength ratio is a constant. Index 'B' is the exponent of the compressive/flexural strength ratio representing the dependence of the compressive strength on the icebreaking resistance.

Using these indices, the procedure to correct the measured icebreaking resistance for variances in ice strengths is simple. The corrected icebreaking resistance component (R_{corr}) is derived from the measured icebreaking resistance component (R_m) using the following equation:

$$\frac{R_{corr}}{R_m} = \left(\frac{\sigma_f\,(target)}{\sigma_f\,(actual)}\right)^A \left(\frac{\sigma_c/\sigma_f\,(target)}{\sigma_c/\sigma_f\,(actual)}\right)^B$$

4. Conclusions

This phase of Indexer development has been completed in two parts. The conclusions for each part of the project may be defined as:

a) Indexer Design Optimisation

- The overall performance of the redesigned Indexer was very promising and indicated that this equipment, if developed further, has the potential to become a standard piece of

testing apparatus for model ice tanks wishing to monitor the relative flexural, shear and crushing strength of the ice sheet.

- The results from the Indexer, tested in the ice sheets on an opportunity basis, showed similar trends to the manual measurement technique results.

- The accuracy of manual ice testing techniques have been observed to be questionable with specific reference to the shearing and crushing failure modes.

- The manual tests for shear and crushing strengths were not suitable to calibrate the shear and crushing plates of the Indexer due to problems experienced with the test equipment.

b) Development of Full Scale Prediction Technique

- It has been demonstrated that the simulation model approach used for the analysis of the ice strength and hull form has the potential to provide a powerful tool. However, further development of the simulation model is necessary to achieve this potential.

- A prototype mathematical model has been developed to evaluate the dependence of ice strength and hull form on model resistance. The mathematical model indicates that the ice flexural strength and compressive strength influences the ice resistance differently for different hull forms. As a result, a correction of the measured resistance from model tests is necessary when the target full scale ice strength properties are not correctly scaled.

5. Recommendations

There are a number of recommendations that have resulted from this research work. These may be summarised by:

a) Indexer Design Optimisation

- The Indexer design and operation should be developed further. This should include providing a fixed and steady platform for the device closer to the model, together with a review of the plate orientation, load cells and ice cutting method.

- The manual techniques, needed for comparison to full scale values, must be developed to permit a more accurate assessment of the crushing and shearing strength properties.

- The Indexer should be re-tested with dedicated ice sheets.

b) Development of Full Scale Prediction Technique

- The performance prediction procedure should be tested and refined with the model and full scale test data for various hull forms.

- The mechanisms of the icebreaking process should be analysed further. A more rigorous and precise descriptive method of the ship/ice interaction should be developed to eliminate, progressively, the assumptions which have been used in the present model.

- The analysis technique should be generalised to extend its application to a variety of hull forms, including non-conventional bow forms.

SOMMAIRE

1. Introduction

L'Indexer est un dispositif de mesure de la résistance mécanique d'une glace modèle, étudié par la Melville Shipping Ltd. en collaboration avec le Laboratoire d'hydraulique du Conseil national de recherches (CNRC) et l'Institut de dynamique marine (IDM). Les premiers travaux, subventionnés par le Centre de développement des transports (CDT), se sont déroulés dans le bassin des glaces du Laboratoire d'hydraulique du CNRC à Ottawa, avec l'aide de M. Timco. Les résultats ont montré que l'Indexer est capable de caractériser une glace modèle et qu'une fois mis au point, il pourrait constituer un instrument intéressant pour le bassin de l'IDM.

Le présent rapport décrit les travaux de mise au point de l'Indexer et expose une méthode permettant d'utiliser les valeurs de résistance enregistrées pour établir de meilleures prévisions sur les performances des brise-glace.

2. Mise au point de l'Indexer

Après des essais préliminaires au Laboratoire d'hydraulique du CNRC, le premier modèle de l'Indexer a été envoyé à l'IDM à St-John's où il a été essayé sur diverses couches de glace. Ces essais ont permis de constater les modifications qui s'imposaient, lesquelles ont, par la suite, été faites par le fabricant.

À l'IDM, l'Indexer a été essayé sur neuf glaces modèles à l'issue d'essais sur modèles réduits. Au cours de chacun des essais, la charge de flexion, d'écrasement et de cisaillement exercées par les plaques de l'Indexer, ainsi que la vitesse d'avancement ont été enregistrees en mode numérique aux fins d'analyse. Les indications de chaque capteur étaient enregistrées à une fréquence d'échantillonnage de 50 Hz. Les glaces soumises à ces essais variaient de 3 à 6 cm en épaisseur et de 15 à 100 kPa en résistance à la rupture en flexion.

Quatre séries de données de caractérisation ont été renregistrées: l'épaisseur de la glace mesurée selon la meethode classique; la résistance de la glace, mesurée selon la méthode classique, puis au moyen de l'Indexer; enfin, la charge appliquée par l'Indexer. Ces données ont été rapportées à la position du dispositif dans le bassin. La courbe de résistance obtenue par l'Indexer semble correspondre assez étroitement à celle établie par la méthode classique. En termes absolus, toutefois, les valeurs de résistance dans l'un et l'autre cas ne correspondent guère en raison de la différence entre les méthyodes employées, l'une procédant par mesure et l'autre par calcul.

Les travaux de mise au point de l'Indexer ont donné lieu à deux constatations importantes qui risquent de remettre en question la possibilité de réaliser en bassin une couche de glace artificielle uniforme présentant des caractéristiques mecaniques constantes.

- plusieurs des couches de glace essayées présentaient une résistance inégale dans chacun des trois axes de chargement;

- les essais classiques ne révèlent pas parfaitement les variations de résistance.

Il est entendu que les variations de résistance de la glace influent plus ou moins sur la performance de tout modèle de coque. Mais l'influence de ces variations sur les résultats obtenus en bassin, et par conséquent, sur les performances réelles prévues des brise-glace, dépendra de la forme particulière de la coque et du mode de rupture qu'elle privilégie. Toutefois, comme une coque de type classique agit à la fois en flexion, en écrasement et en cisaillement, on peut supposer que les variations de résistance de la glace influeront sur tous les résultats d'essais en bassin d'une façon ou d'une autre.

3. Méthode de prévision des performances réelles

Le deuxième volet des présents travaux avait pour but d'évaluer, par une approche théorique, l'influence des caractéristiques mécaniques de la glace sur la résistance globale à l'avancement déterminee par voie d'essais sur modèles réduits en glace uniforme. Partant de cette connaissance, on peut élaborer une formule de correction de la résistance à l'avancement des modèles réduits en fonction des variations de résistance de la glace modèle et, ainsi, établir de meilleures prévisions sur les performances réelles des brise-glace.

En règle génerale, la résistance à l'avancement continu d'un brise-glace dans une couche de glace uniforme est définie par les paramètres suivants:

- la force de rupture de la glace;
- la résistance hydrostatique à l'enfoncement de la glace;
- la vitesse d'avancement.

Des essais en conditions réelles aussi bien que sur modèles reduits ont démontré que la composante "force de rupture" est dans une large mesure déterminée par les caractéristiques mécaniques de la glace. Toutefois, le mode d'action des différents types de coque n'étant pas identique, on peut s'attendre que toute variation des caractéristiques mécaniques de la glace aura une influence différente su la résistance à l'avancement selon le type de coque considéré.

Afin que la résistance a l'avancement puisse être corrigée en fonction des variations de résistance de la glace modèle, il faut évaluer l'importance relative des trois modes de rupture - en flexion, en écrasement, et en cisaillement - dans le cas du modèle de coque étudié. Le meilleur moyen d'arriver à ce résultat est par une formulation mathématique mettant en rapport les caractéristiques mécaniques de la glace et la résistance a l'avancement pour toute une gamme de coques de formes différentes. Aux fins des présents travaux, ces rapports ont été établis d'après les connaissances actuelles des mécanismes en jeu lors de l'avancement dans les glaces.

La formulation des expressions mathématiques s'est faite en trois temps:

- analyse des mécanismes de rupture (glace);
- définition de coefficients de forme (coque);
- application de l'analyse à la prévision des performances des brise-glace.

On a utilisé pour calculer les forces de rupture et les coefficients de forme un modèle informatique conçu pour simuler le mécanisme de rupture des glaces. Des coefficients de forme ont ainsi été définis pour trois coques de brise-glace différentes: celles de l'Arctic, modèle original construit en 1978, la coque Melville de l'Arctic, modifié en 1986 et une coque brise-glace de modèle R.

Les résultats d'analyse montrent que chacune des coques considerées agit différemment. Les coefficients de flexion indiquent que celle-ci sera la force prépondérante de rupture dans les trois cas. D'après les coefficients d'écrasement, la coque originale de l'Arctic est moins efficace a l'écrasement que la coque Melville ou celle de modèle R. La force de cisaillement n'est dans aucun cas un facteur de rupture important, dans les conditions glacielles considérées.

D'après les résultats de la simulation informatique, le rapport entre les forces de rupture en jeu et la résistance de la glace à la flexion et à l'écrasement, pour les couches de glace considérées, peut être représenté assez fidèlement par l'expression suivante:

$$R \sim (\sigma_f)^A \left(\frac{\sigma_c}{\sigma_f}\right)^B$$

L'exposant de chaque facteur varie en fonction de la forme de la coque et de l'épaisseur de la glace. Dans l'expression de la résistance à l'avancement, l'indice "A" est l'exposant de la resistance à la flexion lorsque le rapport entre la résistance a l'écrasement et la résistance a la flexion est constant; l'indice "B" est l'exposant du rapport entre la résistance a l'écrasement et la résistance à la flexion, exprimant la corrélation entre la résistance à l'écrasement et la résistance à l'avancement.

Pour corriger la résistance à l'avancement enregistrée en fonction des variations des diverses valeurs de résistance de la glace, il suffit d'appliquer l'équation suivante, où R_m représente la résistance à l'avancement enregistrée et R_{corr} la résistance à l'avancement corrigée:

$$\frac{R_{corr}}{R_m} = \left(\frac{\sigma_f\ (target)}{\sigma_f\ (actual)}\right)^A \left(\frac{\sigma_c/\sigma_f\ (target)}{\sigma_c/\sigma_f\ (actual)}\right)^B$$

4. Conclusions

La mise au point de l'Indexer a permis de tirer les conclusions suivantes:

a) Perfectionnement du dispositif

- Les résultats obtenus avec l'Indexer modifié sont très prometteurs et permettent de croire qu'une fois perfectionné, ce dispositif pourrait être utilisé couramment dans les bassins d'essai de carènes pour mesurer en continu la résistance de la glace modèle à la flexion, à l'écrasement et au cisaillement.

- Les courbes de résistance obtenues avec l'Indexer à l'IDM à l'issue d'essais sur modèles réduits correspondaient à celles obtenues par les méthodes de mesure classiques.

- L'exactitude des méthodes manuelles de mesure de la résistance à l'écrasement et au cisaillement a dû être remise en question.

- En raison de difficultés éprouvées avec l'appareillage d'essai, les méthodes manuelles de mesure n'ont pas pu être utilisées pour étalonner les plaques d'écrasement et de cisaillement de l'Indexer.

b) Elaboration d'une méthode de prévision des performances réelles

- Il ne fait pas de doute que le modèle utilisé pour l'analyse de la résistance à l'avancement et des coefficients de forme pourrait être extrêmement utile, sous réserve de perfectionnement.

- Un modèle mathématique a été élaboré pour évaluer l'influence des caractéristiques mécaniques de la glace modèle ainsi que de la forme d'une coque donnée sur la résistance à l'avancement lors d'essais sur modèles réduits. L'application du modèle indique que la résistance de la glace modèle en flexion et à l'écrasement influe différemment sur la résistance à l'avancement selon la forme de la coque considérée. Par conséquent, il faut corriger la résistance mesurée lors d'essais sur modèles réduits dans les cas où la glace modèle utilisée ne représente pas fidèlement les caractéristiques de résistance de la glace réelle qu'elle est censée simuler.

5. Recommendations

Les présents travaux ont permis de formuler les recommandations suivantes:

a) Perfectionnement du dispositif

- Il y aurait lieu de perfectionner l'Indexer lui-même ainsi que son fonctionnement. En particulier, revoir l'orientation des plaques de chargement et réétudier les capteurs dynamométriques et le dispositif de découpage de la glace. Il faudrait également prévoir une plate-forme fixe et stable permettant de rapprocher le dispositif du modèle réduit.

- Les méthodes de mesure manuelles nécessaires pour comparer les valeurs enregistrées lors d'essais sur modèles réduits avec les valeurs en conditions réelles doivent être mises au point pour permettre d'évaluer avec plus de précision la résistance de la glace à l'écrasement et au cisaillement.

- Le dispositif devrait être essayé de nouveau sur des couches de glaces produites spécialement à cette fin.

b) Elaboration d'une méthode de prévision des performances réelles

- La méthode de prévision des performances des brise-glace devrait être mise au point à l'aide des données de caractérisation obtenues lors d'essais sur modèles réduits comme en vraie grandeur de différentes formes de coques.

- L'analyse des mécanismes de rupture de la glace devrait être poussée plus loin en vue de parveni à une description plus rigoureuse et précise des interactions glaces-navire qui permettra de remplacer graduellement les hypothèse qui ont servi pour l'élaboration du modèle de prédiction actuel.

- La méthode d'analyse devrait être généralisée pour la rendre applicable à une diversité de formes de coques, y compris les plus spéciales.

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1. INTRODUCTION

Ice tank simulation is frequently used for predicting the performance of icebreaking ships. The natural ice is represented by either artificial ice or natural ice grown in refrigerated basins. The model of the subject ship is then pulled or self propelled through the simulated ice sheet and the resistance is used to calculate the performance of the full scale vessel. This procedure is clearly dependent on the mechanical properties of the model ice and its ability to simulate the required full scale conditions.

Extensive research has been completed on the development of new techniques to improve this simulation. The thrust of this research has been directed at developing the ice crystal structure. Examples are the recent developments of the EGADS dopent [1] and FG-ICE [2] for refrigerated model basins. Less work has been directed at developing a method that will efficiently measure these ice properties or a procedure to use the measured ice properties to improve the prediction of full scale performance from the model test. For example, the ice modulus has been measured for many years and quoted in model test reports, however, despite measurements of ice modulus differing by a factor of two to one, no correction to model resistance has ever been attempted.

Melville Shipping Ltd. (Melville) has been involved with the design and testing of icebreakers for many years. During 1982, Melville was involved in the design of a new bow for the bulk carrier M.V. ARCTIC. The bow design, which was subsequently fitted to the ARCTIC and is known as the 'Melville Bow', involved the analysis of the results, procedures and performance predictions from a number of ice tanks. The ability of each tank to predict the performance of the ARCTIC was significantly influenced by the difficulties associated with the measurement of the mechanical properties of the model ice.

The method currently adopted for measuring the mechanical properties of model ice is the cantilever beam method. This involves cutting, and loading to failure, a cantilever beam cut from the ice sheet. This procedure only measures the flexural strength of the ice, is time consuming and not entirely satisfactory for the large, third generation ice tanks which may be up to 70 m in length.

In response to this problem Melville has developed the concept of a device that will be capable of quickly and easily measuring the flexural, shear and crushing strength of model ice along the entire length of the ice tank. The result of this work was the Ice Strength Indexer.

The Indexer was developed by Melville, in association with the National Research Council's (NRC) Hydraulics Laboratory and the Institute for Marine Dynamics (IMD). The initial development of the Indexer was

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Numbers in brackets designate references listed at the end of the report.

undertaken at the Hydraulics ice tank of the NRC in Ottawa in association with Dr. Timco [3] and sponsored by the Transportation Development Centre (TDC). The results from this work demonstrated that the concept of using the Indexer to calibrate the strength of an ice sheet worked very well and that the Indexer could become a useful and time saving tool for the IMD ice tank.

The development of the Indexer described above included the initial design and correlation between the flexural strength of the ice and the output from the Indexer bending plate [4]. Important recommendations from the study were;

1. Additional model tests should be conducted to calibrate the Indexer outputs to the shear and crushing strengths of the ice.

2. Hull form coefficients should be developed to evaluate a particular bow's tendency to fail the ice in crushing, shearing and bending. These may then be used to correct the model test results for model ice mechanical properties that do not correctly represent the required full scale conditions.

This report describes the work undertaken to address these two recommendations. In addition. the report also describes the design modifications to the Indexer based on the results of a series of preliminary tests at the IMD tank in St. John's, Newfoundland.

The report is divided into two sections. The first section describes the preliminary model tests at St. John's and the Indexer redesign. This element of work was jointly funded by Melville and IMD and includes the redesign and construction of the Indexer, model tests and some correlation between the Indexer output and the model ice properties. The second section describes the procedure that may be used to modify the model scale resistance to reflect the variations in ice strength. This element of the work has been funded by the TDC.

2. INDEXER DESIGN OPTIMISATION

2.1 General

Following the completion of the initial design and model testing of the Indexer at the NRC Hydraulics Laboratory in Ottawa [3], the Indexer was shipped to St. John's and a series of ice sheets were used to assess the performance of the Indexer in the IMD tank. These tests resulted in a number of design modifications which were then undertaken by the original fabricator of the Indexer in Ottawa. The modified Indexer is shown in Figure 2.1.

2.2 Design Modifications

The Indexer was initially tested in three ice sheets at IMD to evaluate its performance in the tank. The tests revealed a number of problems that needed to be resolved prior to the Indexer being used in constant service. These were:

1. The pneumatic drive motors for the drill bits required large volumes of compressed air which were not directly available from the IMD tank carriage.

2. The drill chucks used to hold the drill bits were not balanced and too heavy for the pneumatic motor bearings. This caused excessive vibration that detracted from the value of the data.

3. The bending plate was not yielding predominant fracture peaks that could be easily identified.

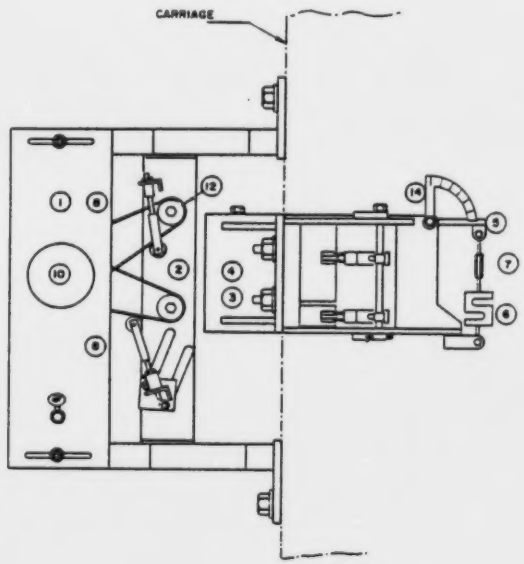
4. The shearing plate was exhibiting a large bending failure component that detracted from the shear failure output.

The original selection of pneumatic motors was based on an air supply available at the NRC Hydraulics tank in Ottawa. A similar air supply is not available at the IMD tank and during the initial IMD tests the air was supplied by three air compressors that were temporarily mounted on the towing carriage. This caused problems with monitoring each compressor and ensuring that the compressor tanks were suitably charged prior to each test. The arrangement has been modified to a single electric motor driving two belts which in turn drive the two drill bits. This has proved to be a significant improvement over the original pneumatic system.

The drill chucks were considered to be excessively heavy and caused unacceptable vibrations. These were replaced with a simple sleeve arrangement and locking screws to secure the drill bits. In addition, bearings were added around the vertical drill shaft, directly below the electric motor, to minimise the transverse loads transmitted to the motor bearings from the drills.

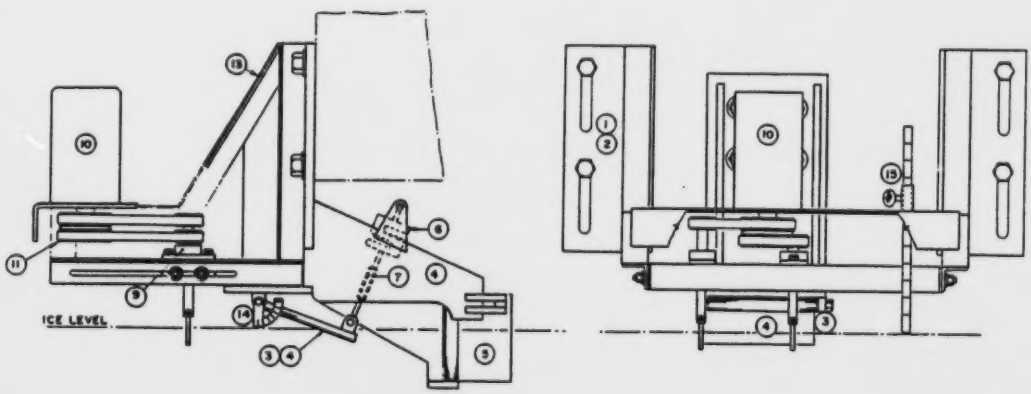
FIGURE 2.1

THE MODEL ICE INDEXER



LIST OF ITEMS

1. DRIVE MOTOR SUPPORT FRAME
2. CUTTERS SUPPORT FRAME
3. SHEARING PLATE ASSEMBLY
4. BENDING PLATE ASSEMBLY
5. CRUSHING PLATE ASSEMBLY
6. LOAD CELL (3)
7. TURNBUCKLE (3)
8. BELT TENSIONER (2)
9. BEARING ASSEMBLY (2)
10. DRIVE MOTOR
11. 3" DIA. PULLEY
12. 1 1/2" DIA. PULLEY (2)
13. PERSPEX SPLASH GUARD
14. ANGLE INDICATOR (3)
15. CLEARANCE INDICATOR



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Nominally conventional cantilever beam tests are conducted on a beam, cut from the ice sheet with the overall length of five times thickness and a breadth of 1.5 times thickness, resulting in breadth and thickness properties of 5, 1.5 and 1. During the initial tests at the Hydraulics tank in Ottawa, the cantilever beam was made wider to maximise the downward force to break the beam, and ensure a good force record was obtained. Following the success of these preliminary tests it was decided to reduce the ice beam width to represent, more closely, the conventional geometry. Unfortunately, the reduction of the bending plate width also resulted in a reduction of the absolute force necessary to break the ice cantilevers, and it became more difficult to distinguish the force peaks from the background noise. The background noise is thought to be caused by two phenomenon; the contact between the broken ice piece, after fracture, and the Indexer cantilever bending plate and; the turbulence of the water around the plate as it moves through the tank. These forces were reduced by ensuring that the Indexer plates were tested as high as possible out of the tank. The final solution was a compromise between the desire to have a wide plate that would generate predominant load peaks and beam sizes that would compare with the manual measurement technique. As a result, the Indexer was redesigned to accommodate a range of plate widths. The selected plate widths were 0.127 m (5 inches), 0.0762 m (3 inches) and 0.0381 m (1.5 inches). Both the flexural and shear plate were inclined at 30^{o} to the horizontal for all the model tests. The crush plate angle was 60^{o} to the direction of travel. The drill bits were positioned in their aft most location in a .102 m (4 inches) in front of the inclined plates.

The output from the shear plate exhibited a significant flexural failure component that was detracting from the shear failure data interpretation. To improve this data output it was decided to reduce the width of the shear plate. As with the bending plate, it was decided to design the Indexer to accommodate a range of shear plate sizes. The plate sizes fabricated were, 0.0381 m (1.5 inches) and 0.0127 m (0.5 inches).

The crushing plate was not modified from its original configuration

2.3 Model Tests

2.3.1 Model Test Results

The modified Indexer was temporarily mounted on the IMD ice tank towing carriage for testing. To date, [17] tests of the Indexer have been conducted at IMD using [9] ice sheets. All of these tests were made on an opportunity basis after the completion of other dedicated model tests. During each test, the load cell output signals from the Indexer's bending, shear and crushing plates and the speed of the towing carriage were recorded digitally for subsequent analysis. The data was recorded at a sampling rate of 50 HZ for each channel. The test data which has been compiled includes various ice thickness and strength conditions, ranging from 3 cm to 6 cm in thickness and from 15 to 100 kPa in flexural strength as measured using the cantilever beam method [7].

To facilitate the analysis of the Indexer output, a computer programme has been developed by Melville to convert the ice force spectra, measured from the Indexer's load cells, automatically into the corresponding ice

strength values as a function of time or the position in the tank. The ice strength calculation method from the Indexer output is described in detail in Appendix 1. The major peaks of the ice force spectra are scanned and the magnitude of each peak is captured by the computer programme. The time differences between the adjacent major peaks in the spectrum are also measured to determine the cantilever beam length and shear surface area which are used for deriving the corresponding flexural and shear strengths. Due to the configuration and breaking pattern of the Indexer it will not break the ice in either pure shear, bending or crushing. As a result the strengths generated by the instrument should be considered, as with any other test of this kind, as representative of these absolute strength values equal to them.

Figures 2.2 and 2.3 illustrate typical flexural strength results obtained from the Indexer. Four outputs are plotted; the manually measured ice strength, the derived strength from the Indexer, the Indexer force output, and the manually measured ice thickness. The data is plotted as a function of position in the tank. Using this figure the recorded ice force spectrum may be compared with the manually measured ice strength and thickness data. The ice strength calculated by the Indexer appears to correlate in terms of the overall trend, with the manual ice strength record. The absolute values of the two strengths are different and reflect the measuring and calculation procedure used by each method and the time delay between the manual measurement and Indexer test run. The next stage of the analysis is to correlate these two outputs with dedicated ice sheet tests to obtain more consistent absolute values.

Figures 2.4 and 2.5 display the measured shear strength results from two Indexer runs. For the run shown in Figure 2.4, a manual shear strength record is available and is found to be comparable in absolute terms to the Indexer output.

Two examples of the compressive strength record are shown in Figures 2.6 and 2.7. It may be noted that Figure 2.6 exhibits a significant difference in ice compressive strength at various positions along the ice sheet. Unfortunately it was not possible to manually measure the ice crushing strength during these tests.

A copy of all the Indexer outputs collected from the initial tests are given in Appendix 2.

2.3.2 Discussion

A review of Figures 2.4 to 2.7 result in two major findings from this work that may significantly affect the capability of an ice tank to fulfill its objective of simulating a uniform, consistent ice sheet.

1. A number of the ice sheets tested showed significant variations in the crushing, shear and flexural strength.

2. Conventional testing of model basin ice for strength cannot always take into account strength variations that may exist along the tank length.

FIGURE 2.2

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 4-AUG-1987 09:55:39

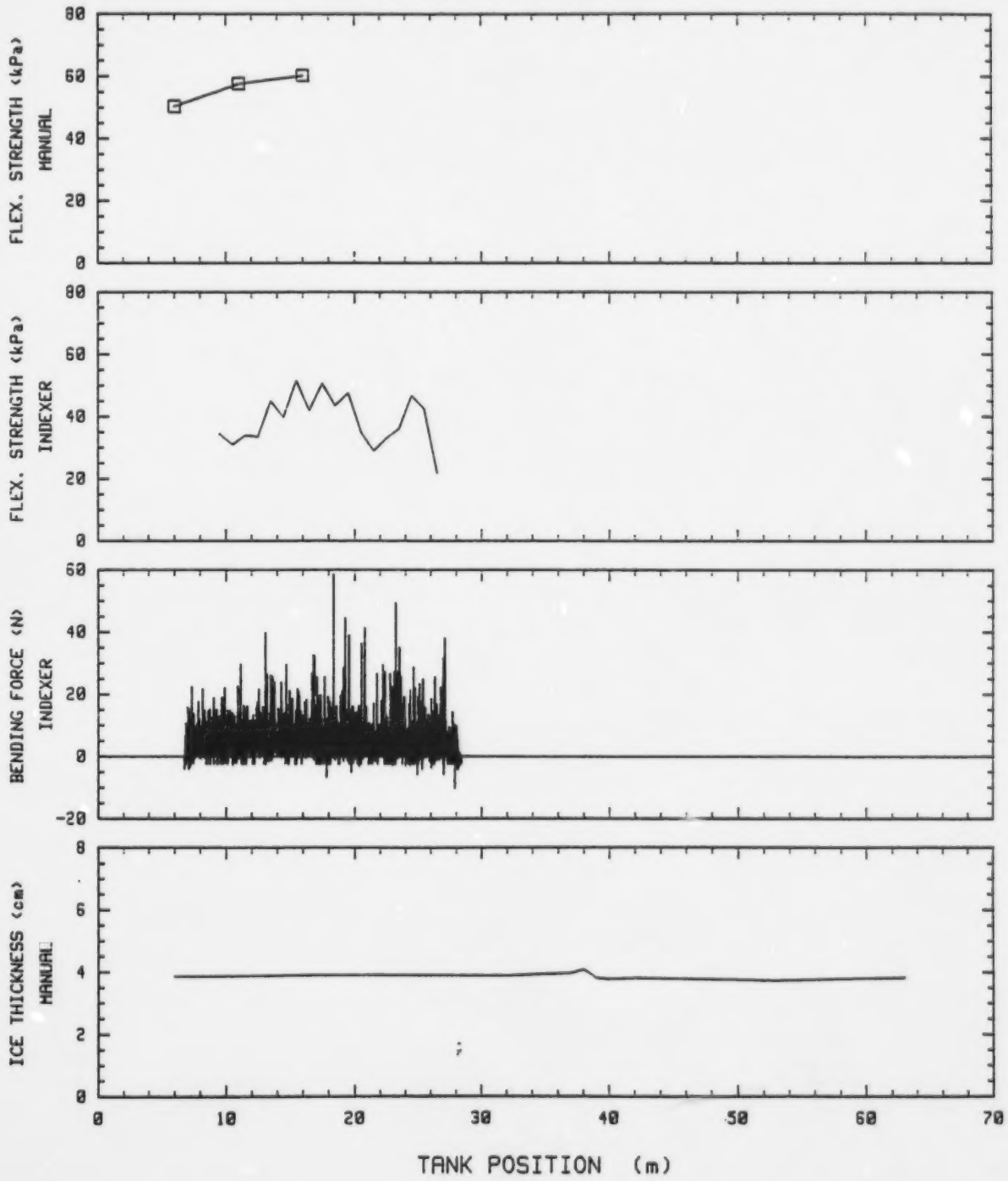

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FIGURE 2.3

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 7-AUG-1987 15:42:47

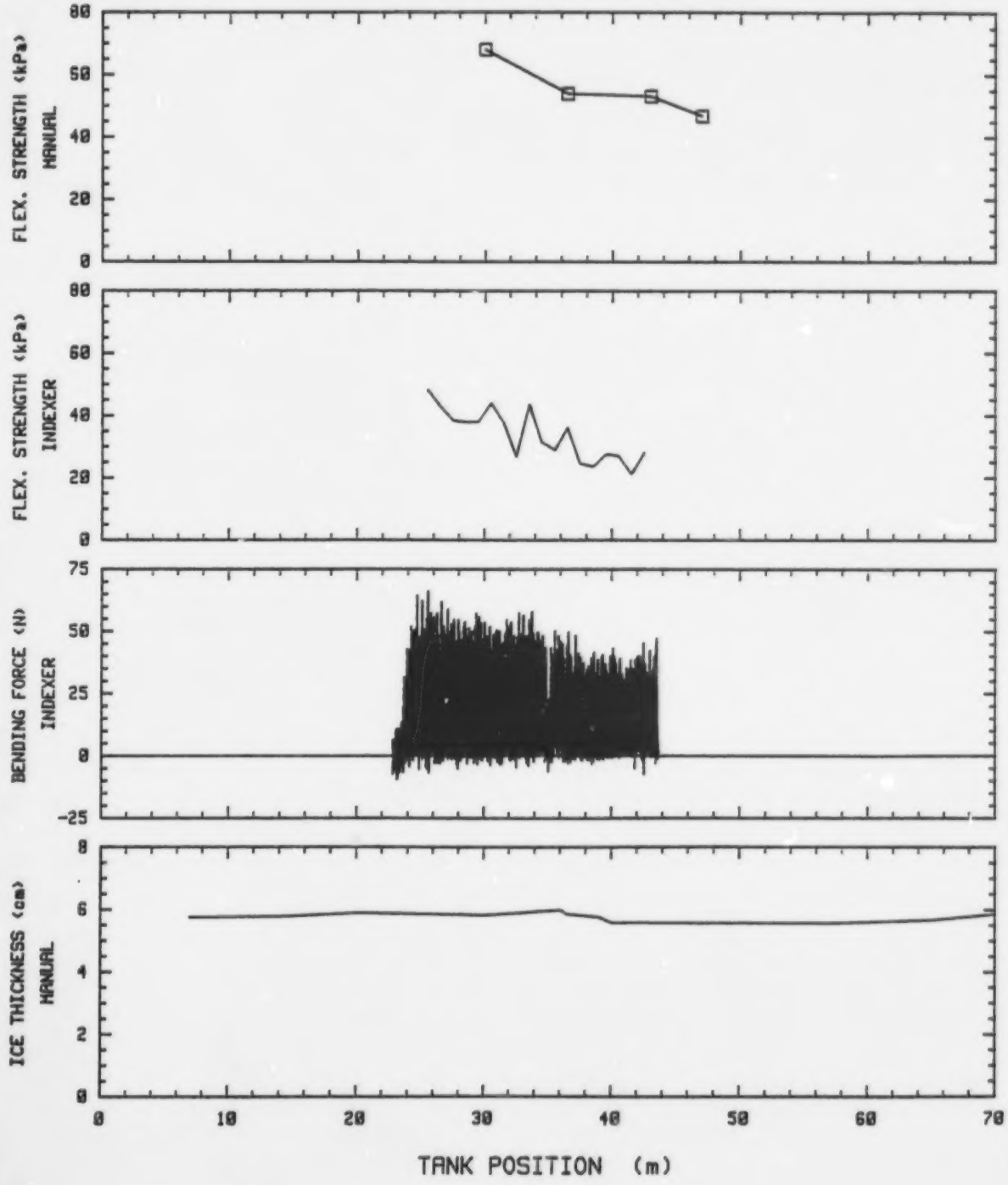

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FIGURE 2.4

ICE SHEET DATA - SHEAR STRENGTH

RUN 6-OCT-1987 18:03:03

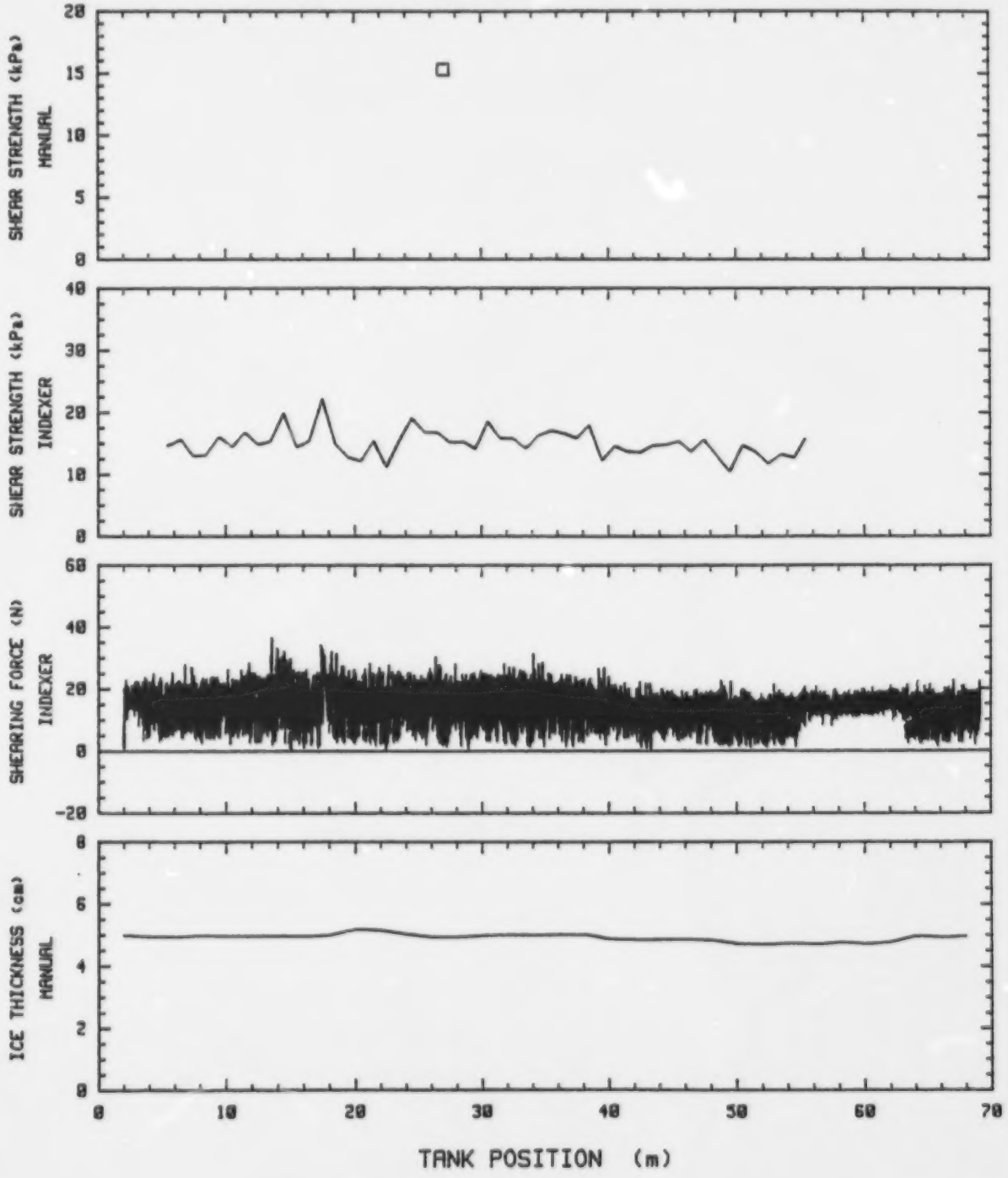

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FIGURE 2.5

ICE SHEET DATA - SHEAR STRENGTH

RUN 15-SEP-1987 12:33:15

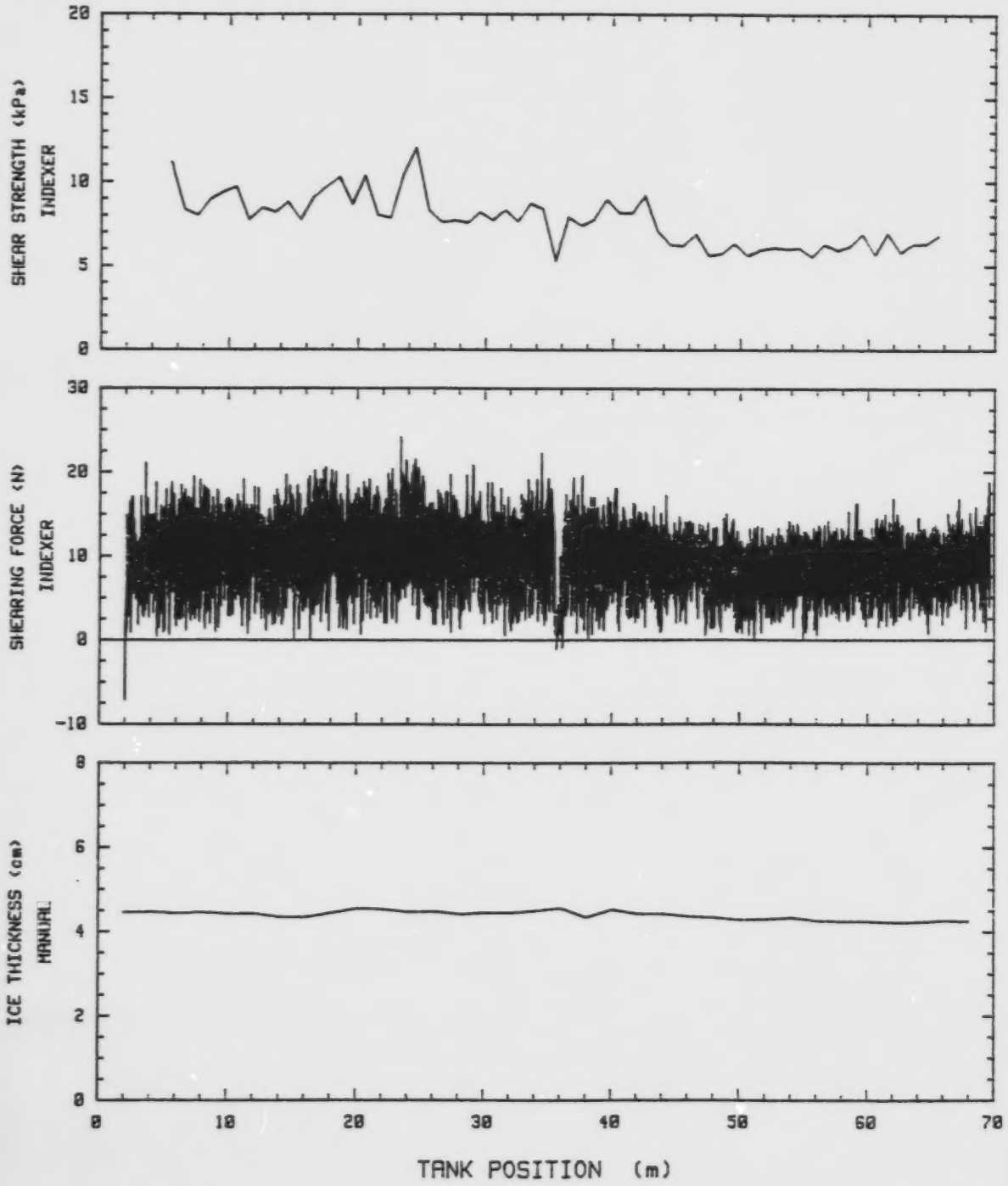

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FIGURE 2.6

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 22-SEP-1987 12:00:19

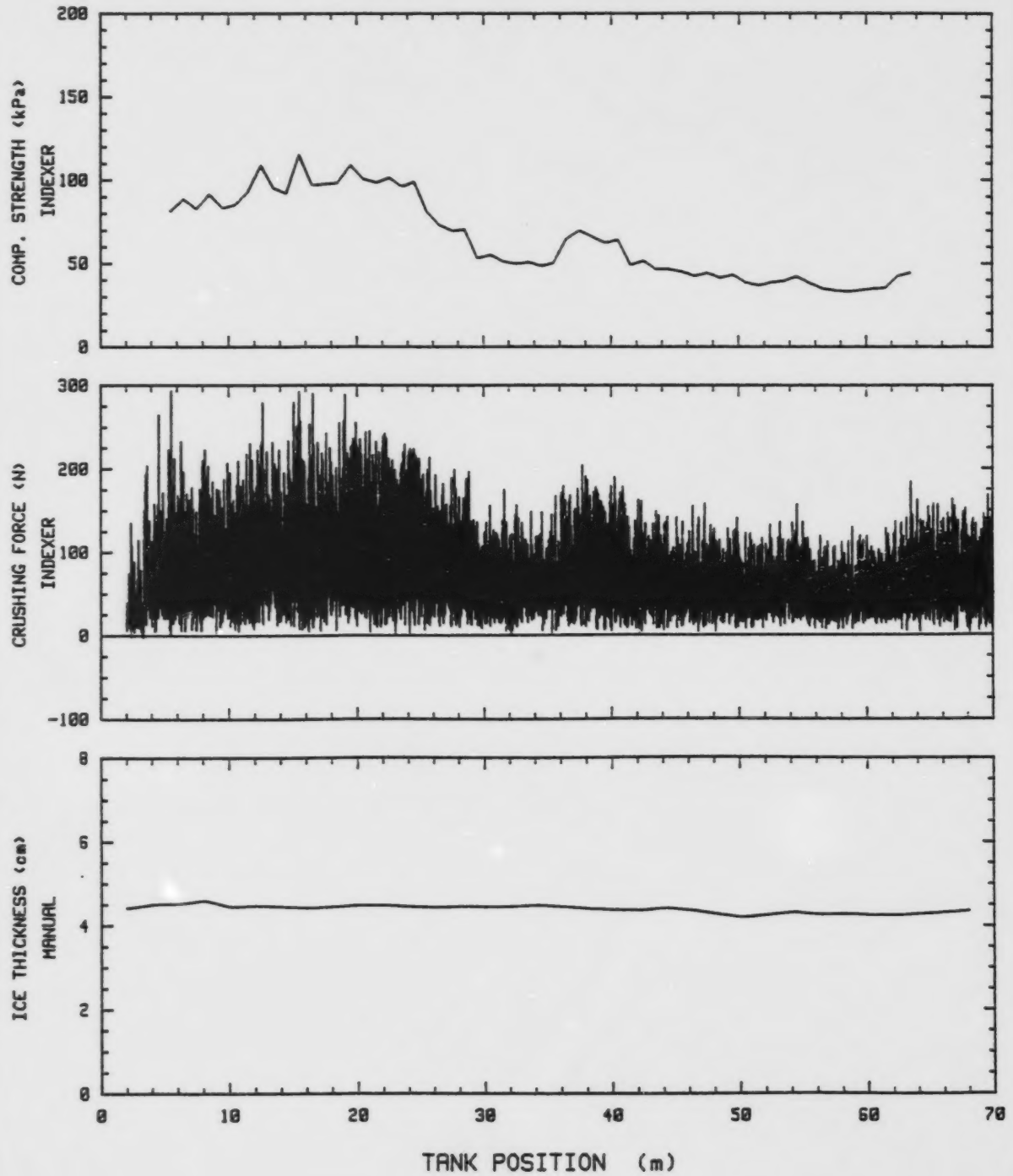

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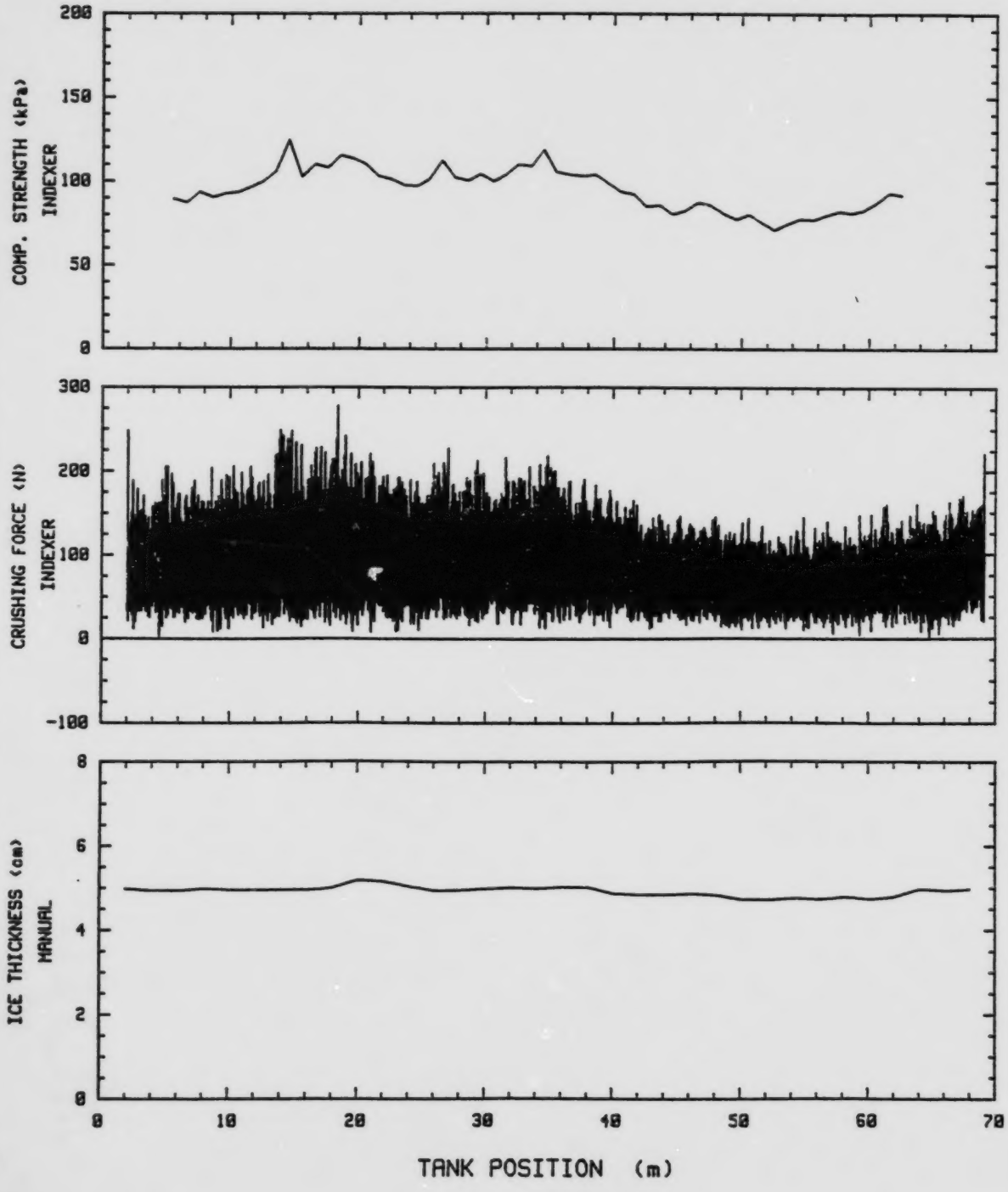
FIGURE 2.7

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 6-OCT-1987 18:03:03



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Although the variation of ice strength will, to some degree influence all bow forms, the extent to which these variations will influence the resistance of a particular model, and therefore the prediction of the full scale performance of a ship, will depend on the type of bow and the mode with which it breaks the ice. However, since a conventional bow will break ice in a combination of bending, crushing and shearing, it can be anticipated that the majority of model tests may be affected in some way.

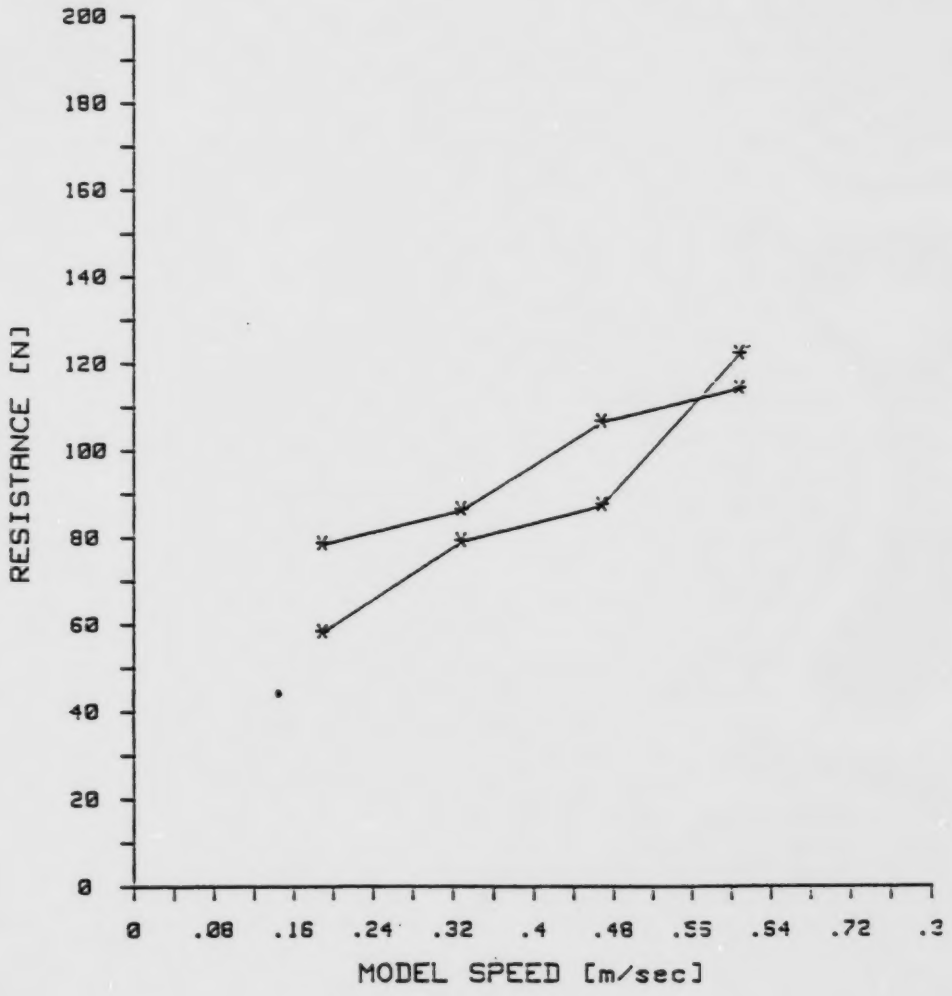
A recent example of how this effect may be manifesting itself during model tests are the preliminary results from a pair of tests recently conducted for TDC to investigate the friction coefficient. The same model was tested in seemingly 'identical' ice sheets and resulted in the data presented in Figure 2.8. The data shows that two speeds, 0.33 m/sec and 0.61 m/sec, were repeated within 10 percent. However, the two other speeds varied by up to 34 percent. A review of the ice sheets properties, measured using conventional equipment, showed that both ice flexural strength and thickness were duplicated within 2 mm and 1 kPa. The reason for this difference between two otherwise identical tests is thought to be associated with the mechanical properties of the ice that could not be measured using the standard procedures, such as the crushing and shear strength and the elastic modulus. These tests demonstrate the potential variability of different ice tests and highlight the need for better measuring techniques for the model ice.

The data analysis from the Indexer has focused on the evaluation of ice strength, i.e. the flexural, crushing and shearing strength of the ice. Another important parameter which is not measured directly, but which we believe may be deduced from the flexural load failure output, is the elastic modulus of the ice. The elastic modulus is routinely measured by loading the ice sheet with known forces and measuring the deflection. This is done prior to the model test. The proposed method for obtaining the elastic modulus from the Indexer is to monitor the area under the force/time curve collected from the Indexer flexural bending plate. This area will be directly related to the elastic modulus, which is defined by the slope of the force deflection relationship. A larger area will be associated with more elastic ice and a smaller area, conversely, will be associated with more brittle ice.

The scope of this project has not permitted this analysis to be developed further than recognising the Indexer could be used to measure elastic modulus. This work should form part of any subsequent analysis.

FIGURE 2.8

COMPARISON OF TWO IDENTICAL
TESTS FROM THE FRICTION PROGRAM AT IMD



Target strength = 19 kPa
Target thickness = 50 mm
Friction coeff. = 0.063

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3. DEVELOPMENT OF FULL SCALE PREDICTION TECHNIQUE

3.1 General

The full scale performance of a ship is simulated at model scale using a set of well established similarity laws [8]. These generally accepted similarity laws required that the model ice is scaled to the natural ice conditions by a geometrical scaling factor (λ). This is the same scaling factor used for the model. If both the model and model ice are scaled correctly, the full scale resistance can be directly related to the model scale resistance by the cube of the scale factor (λ^3). However, as discussed in the previous section, since the strength of the model ice cannot be consistently reproduced to specific natural ice conditions, the results obtained from model experiments have to be corrected.

It is believed that the Indexer, described in Section 2, can be developed to accurately monitor the strength of the ice. The objective of this element of the project is to assess, through a theoretical approach, the effects of the ice strength on the level ice resistance obtained from model scale experiments. This may then be used to develop a practical correction procedure to compensate the measured model resistance for variations in the ice strength and thereby produce more accurate full scale resistance predictions.

Generally, the resistance to a ship operating in the continuous level icebreaking mode can be divided into the following components:

- icebreaking,
- ice submersion, and
- velocity.

The icebreaking component refers to the energy required for the ship to crush, bend and break the ice. The ice submersion component represents the energy required for the ice displacement and cusp rotation after the ice is fractured and separated from the ice sheet. The velocity term accounts for the augment of the total resistance due to the speed of the ship and the hydrodynamic resistance experienced in open water transit.

Experiments at full scale, together with model scale resistance tests, have shown that the 'icebreaking' component of resistance is strongly affected by the strength of the ice [9]. However, due to the different icebreaking mechanisms that will occur for different bow shapes, any variation of ice strength from the assumed values may affect hull forms differently. For example, if a bow form which exhibits extensive crushing, such as the original ARCTIC bow, is tested in model ice that has incorrectly scaled crushing strength, the resultant influence of crushing strength on the model resistance will be larger than for a bow that exhibits less ice crushing, such as a Melville or Spoon bow.

To ensure that the correct modifications are made to resistance for variations in model ice strength it is necessary to evaluate the preponderance of each type of bow form to break ice in flexure, shear and crushing. The most appropriate method to evaluate these values is to

develop a mathematical expression that attributes a specific relationship between resistance and ice strength for a range of bow forms.

Since the objective of this work is not to use hull form coefficients in semi-empirical equations, but to define more precisely the icebreaking component of resistance, the approach which has been adopted is to develop coefficients based on our present understanding of ship/ice interaction mechanisms.

The development of the expressions and description of the formulations have been divided into three parts:

- analysis of ice breaking mechanisms,
- development of hull form coefficients, and
- application of the analysis to the full scale performance prediction.

3.2 Analysis of Icebreaking Mechanisms

The breaking mechanisms at the bow of an icebreaker are very complex and difficult to represent numerically unless a number of assumptions are made. All of the existing numerical formulations contain one or more of these assumptions which simplify the simulation of the interaction and permit an estimation of the icebreaking forces and ice floe movement. Typical assumptions used by these methods include:

- level homogeneous ice,
- uniform mechanical properties,
- constant cracking and breaking patterns at the bow,
- calculation based on static fracture which is then augmented by a dynamic correction factor,
- breaking only occurs at the waterline,
- the effects of ship motions, such as roll, pitch and heave, are negligible or included in the correlation constants.

The general approach to define the icebreaking mechanisms at the bow is to resolve the discrete static problem of a finite part of the hull impacting an ice edge. This is then integrated along the waterline and results in a total longitudinal force. Some authors [11] develop this further by defining two different forms of interaction, one resulting from contact at the stem and the second a more general expression representing contact over the remainder of the bow. The majority of these formulations have been derived to predict the absolute performance of an icebreaker.

The objective of this report is to develop the necessary formulations to predict the preponderance of each failure mechanism associated with a specific bow form. This is a fundamentally different approach and required the development of a series of expressions that, in a relative sense, define the flexural, shear and crushing failure occurring at the bow of an icebreaker. The resultant formulations have been integrated into a computer program and used to simulate an incremental advance of a bow into an ice sheet. At each increment the ice/hull interaction forces are

calculated together with a new contact area associated with the crushing and shearing strength of the ice. The formulations are discussed in the following notes and defined in detail in Appendix 3.

The program assumes a general ice interaction, as shown schematically in Figure 3.1. The ice sheet is characterised by its thickness and mechanical properties represented by the compressive, shear and flexural strength. Constant ice thickness, strength and elasticity are assumed throughout the ice sheet. A total of ten different initial ice edge conditions are simulated in the program. These conditions are illustrated in Figure 3.2, each of which represents an initial contact with the ice at different positions along the bow, from the stem to the shoulder. The three contact positions shown in Figure 3.2 are presented using the computer program graphics which are displayed on the screen during the program execution.

Although it is probable that, for a conventional bow in level ice, hull contact will occur predominantly in specific areas, for example the stem and the shoulder, the program assumes that the bow is uniformly contacted with the ice. This is considered acceptable at this stage of development, but should be reviewed in any future work.

The failure mechanism associated with each of the ten positions along the bow are calculated independently of each other.

The ice is assumed to crush and deflect under the action of the bow which is progressively moved into the ice edge as shown in Figure 3.1. Equations of vertical, longitudinal and horizontal forces are developed for each increment of advance into the ice sheet based on the new contact area and the failure criteria of the ice.

The movement of the bow into the ice sheet will develop a contact surface and associated vertical and horizontal forces determined predominantly by the ice crushing condition. The force is assumed to be normal to the hull surface and equal to the product of the ice compressive strength and the corresponding effective contact area. The crushing conditions are obtained numerically from the bow geometry and the bow's instantaneous position relative to the ice edge. The vertical deflection of the ice due to bow load is also considered in determining the crushed condition of the ice. This is accomplished by using the load/deflection relationship of the ice sheet taken from the analytical results of Nevel [12] for a semi-infinite plate on an elastic foundation.

At each increment of advance the forces are compared to the failure criteria of shearing and bending. Depending on the hull geometry and ice condition, the ice may develop multiple shear failures prior to a bending failure. The shear line is considered to be vertical through the ice and defined by the bow waterline. In the event of shear failure the ice is assumed to separate from the unbroken ice sheet and a new ice edge condition is defined. If the ice forces developed by crushing do not exceed the shear failure limit load, then the ice will be deflected progressively until a bending failure is developed.

FIGURE 3.1

SHIP/ICE INTERACTION MODEL

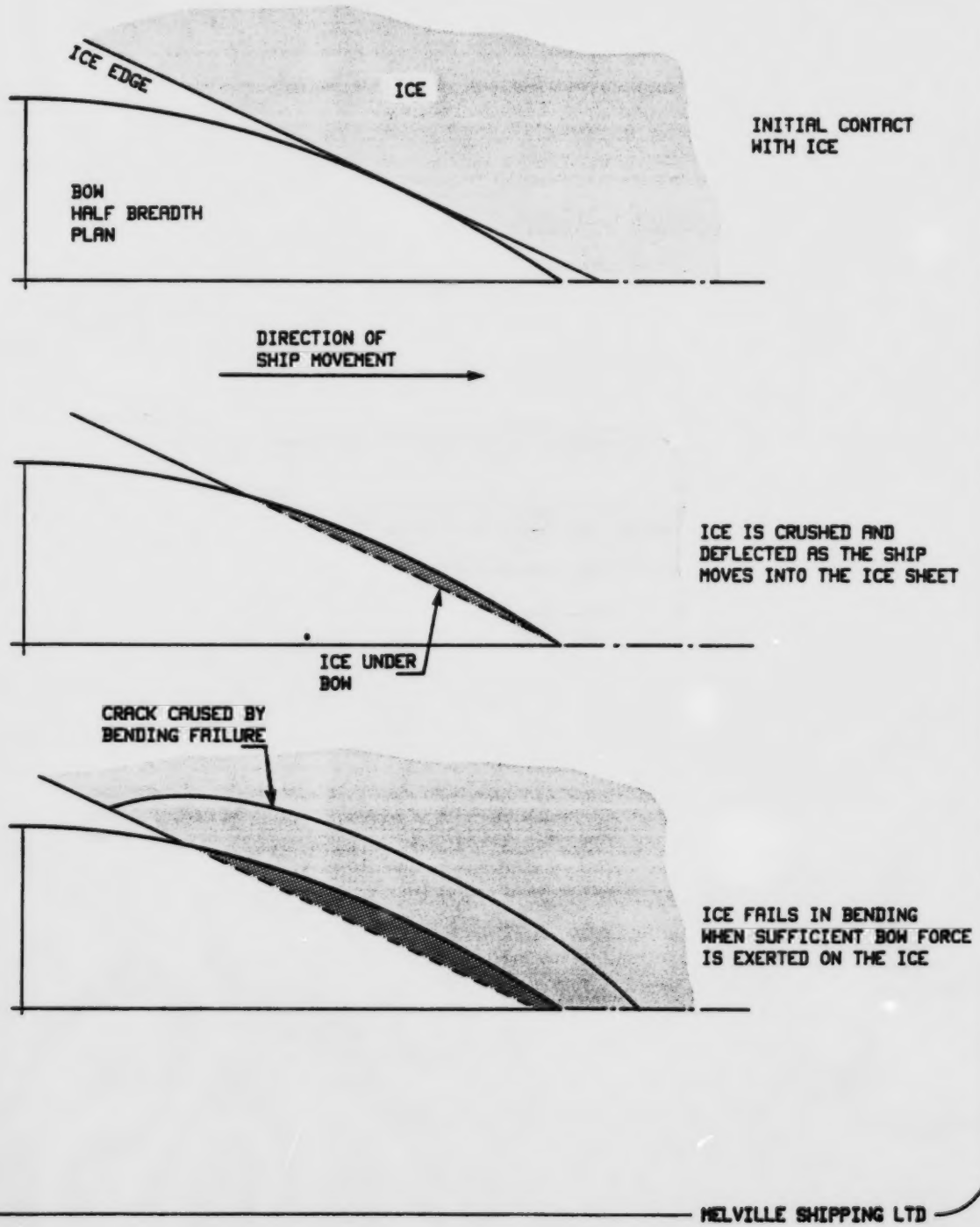

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FIGURE 3.2

ASSUMPTION OF ICE GEOMETRY AND CONTACT CONDITIONS

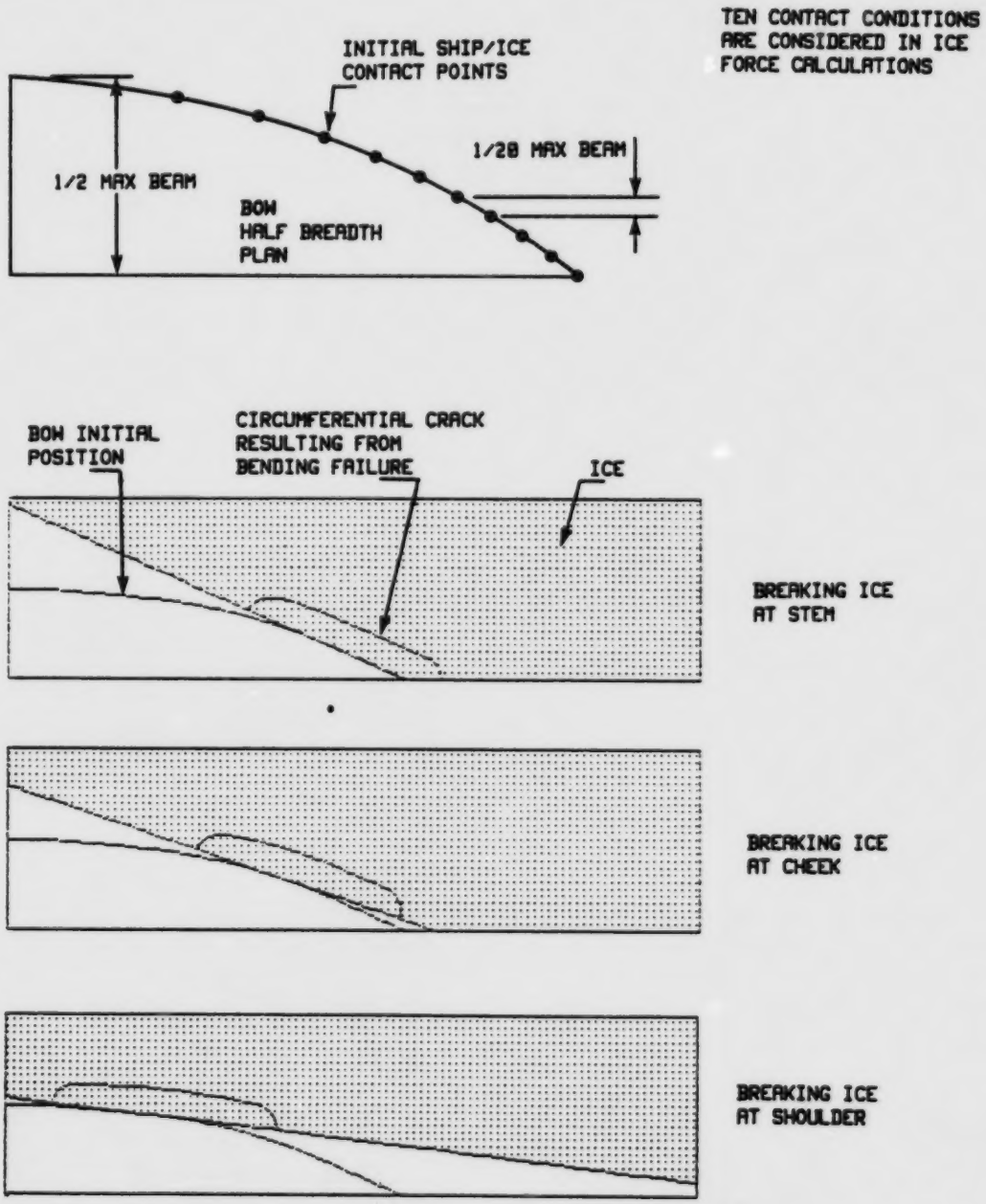

TEN CONTACT CONDITIONS ARE CONSIDERED IN ICE FORCE CALCULATIONS
INITIAL SHIP/ICE CONTACT POINTS
1/20 MAX BEAM
1/2 MAX BEAM
BOW HALF BREADTH PLAN
BOW INITIAL POSITION
CIRCUMFERENTIAL CRACK RESULTING FROM BENDING FAILURE
ICE
BREAKING ICE AT STEM
BREAKING ICE AT CHEEK
BREAKING ICE AT SHOULDER

Figure 3.3 illustrates the two possible load/failure scenarios. The curves define the hull normal force versus the contact area between the ice surface and the ships hull. It may be noted that if the ship speed was simulated then the contact area would be a time dependent function as the ship moved into the unbroken ice.

Two failure modes are represented in the figures, the bending failure, which is independent of contact area, and shown as a horizontal straight line, and the shear failure which is proportional to contact area. The upper figure in Figure 3.3 shows the case when, due to ice hull contact and the associated local crushing, a hull normal force is built up to a point where it equals the shear failure criteria. At this point the ice will fail, the hull normal force will drop to zero and the process repeats itself until the local crushing forces build up sufficient contact area to fail the ice in bending.

In the lower figure, the hull normal forces do not reach the shear failure criteria and no shearing takes place prior to bending failure.

The bending failure criterion is determined primarily using the limit load established analytically by Carter [11] for a vertical force applied on an ice edge. The criterion also includes the increase in capacity of the ice due to the presence of in-plane or horizontal stresses in the ice. The in-plane stress is estimated from the horizontal component of the bow force on the ice. In the event of a bending failure, a crack is simulated and the ice within the crack is considered to be broken off from the remaining ice sheet. The crack is described by a line having a fixed distance from the contact edge of the hull and ice, at the waterline, at the time of failure. The crack distance from the hull is taken to be a fraction (0.3) of the ice characteristic length, this is based on observations of icebreaking patterns at model and full scale. The length of the crack is defined by the length of the contact between ice and hull.

Each point on the bow is used to derive a series of crushing and shearing interactions until bending failure occurs. A representation of relative icebreaking resistance is then obtained by calculating the ratio of the energy expended by ice crushing, shearing, and bending, to the area of broken ice.

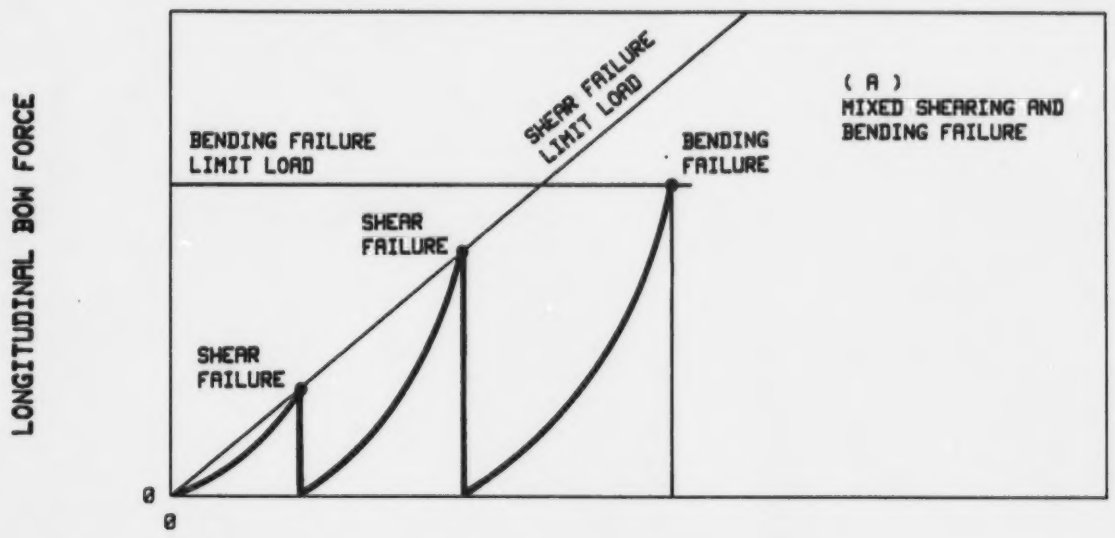
The ice longitudinal resistance force is assumed to be symmetrical with respect to the centre line and, therefore, only the ship/ice interaction on one side of the ship is simulated.

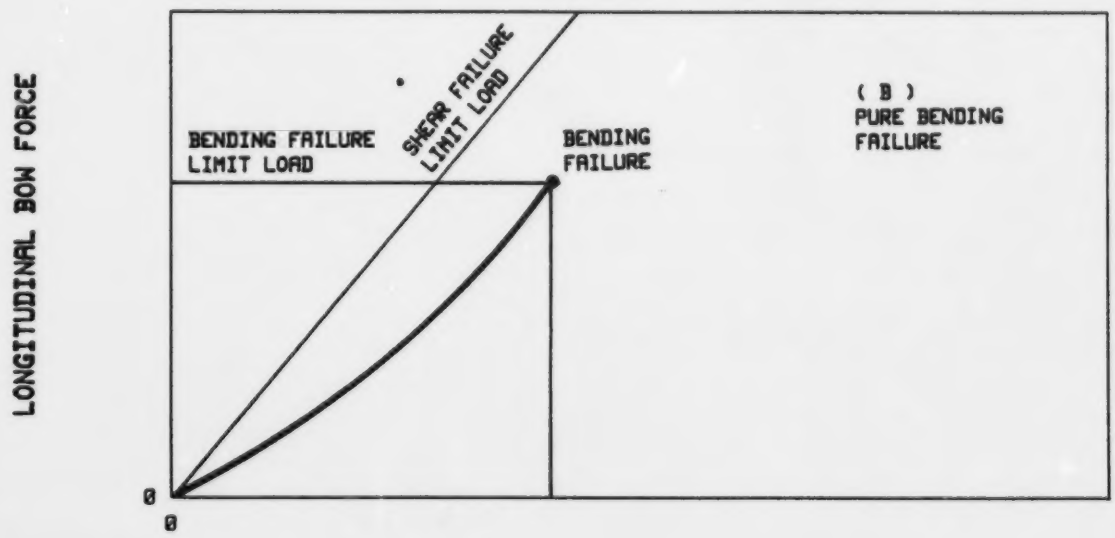
3.3 Development of Hull Form Coefficients

The objective of a hull form coefficient, as it is commonly used, is to characterize the shape of a hull in a simplified form so that it may be integrated into a semi-empirical equation. There have been a number of these coefficients developed over the past few years [13; 14] which are broadly based on the calculation of the 'hull normal vectors' at the waterline of the icebreaker and averaged or integrated over the length of the bow.

FIGURE 3.3

SHEARING AND BENDING FAILURE CRITERIA





Three hull form coefficients have been developed to describe the ice-breaking effectiveness of a specific bow:

- crushing coefficient.
- shear coefficient, and
- bending coefficient.

The crushing coefficient is used to assess the likelihood of the ship/ice interaction to include crushing, and is defined as the ratio of the volume of the crushed ice to the total volume of the ice being broken by the ship. Similarly, the shearing and bending coefficients are defined respectively as the corresponding ratios in association with the shearing and bending failures.

A computer model has been developed to simulate the icebreaking process based on the analysis as described in subsection 3.2, and is used to derive the icebreaking forces and hull form coefficients. The bow geometry at the waterline is defined at a number of discrete points by the half ordinates at the waterline and flare angles. Examples of hull form coefficients have been developed for three icebreaker hull forms; the original ARCTIC built in 1978, the modified ARCTIC fitted with a Melville Bow in 1986, and an R-Class hull form. The hull waterline and flare angles for each of these bow forms are compared in Figure 3.4. The R-Class hull form has been generated with the same breadth as the M.V. ARCTIC.

The computer model has been exercised with varying combinations of ice thickness and strength and thickness conditions for each of the three bow forms. The calculations were made for a model scale of 1:30 based on 500 kPa flexural strength, 1,000 kPa shear strength and 1,500 kPa compressive strength, and one meter ice thickness at full scale. Each of these parameters were then varied within at least plus and minus 50 percent to assess the sensitivity of the variable with respect to the icebreaking force. The elastic modulus (E) was kept constant for all runs at an equivalent of 1,000 mPa full scale, corresponding to an elastic modulus to flexural strength ratio of 2,000 for the base case condition. The base case selected is considered to be one of the commonly used model ice conditions in ice tanks.

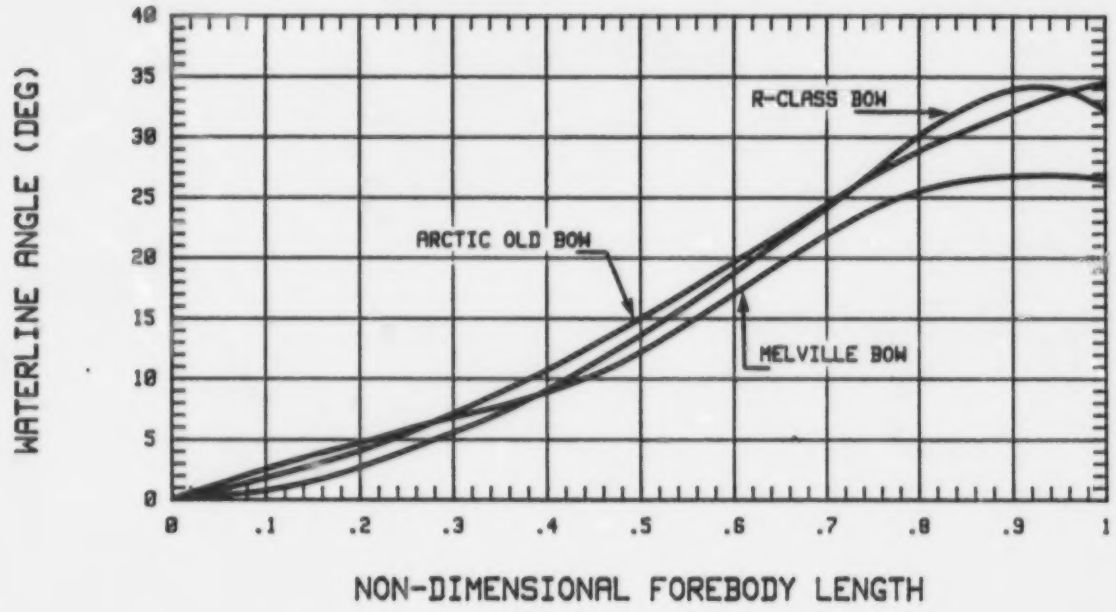
Table 3.1 shows the computed hull form coefficients of the three bow designs at different ice conditions. The resultant analysis shows that the icebreaking action of each bow is different, as shown in Table 3.1. Based on the crushing coefficients the old bow is less efficient in icebreaking than the Melville Bow or the R-Class bow. The bending coefficients show that the ice will be broken, predominantly by bending, by all three bows. The shear failure mode was not found to be a primary icebreaking mode for the three bows within the range of the ice conditions being investigated.

3.4 Full Scale Performance Prediction Procedure

The prediction procedure presently used in ice tanks is to follow the Froude scaling laws, with an additional step to allow for appropriate

FIGURE 3.4

WATERLINE AND FLARE ANGLES
OF VARIOUS BOW DESIGNS



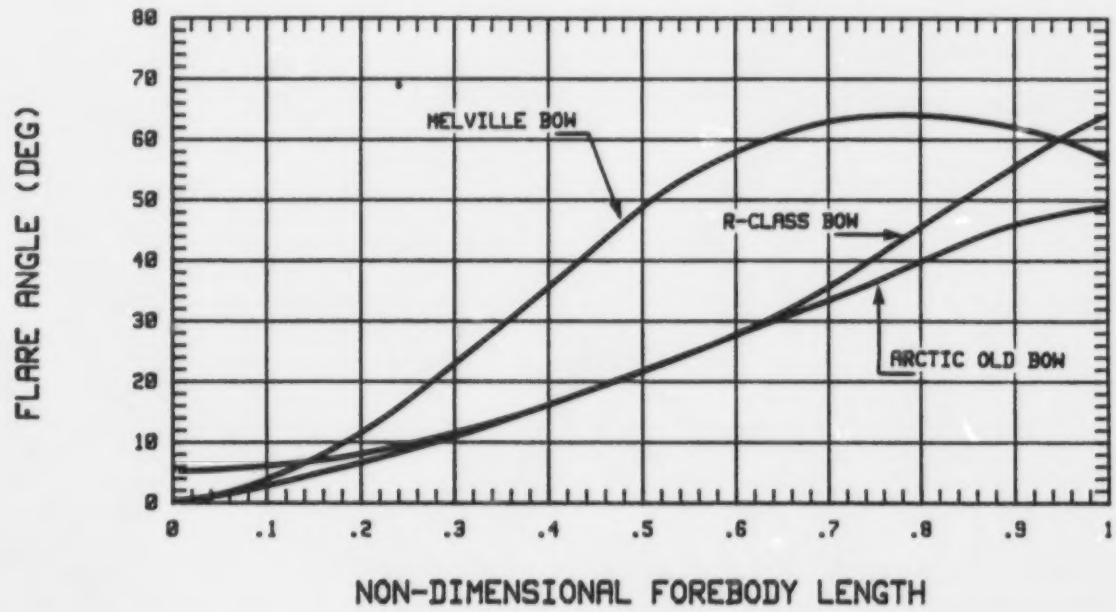


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TABLE 3.1

CALCULATED HULL FORM COEFFICIENTS

	ARCTIC (Melville) BOW	OLD ARCTIC BOW	R-CLASS BOW
(ice thickness: 0.5 m)			
Crushing coeff:	0.000086	0.00049	0.000289
Shearing coeff:	0.	0.	0.
Bending coeff:	0.999914	0.99951	0.999711
(ice thickness: 1.0 m)			
Crushing coeff:	0.000213	0.001506	0.000819
Shearing coeff:	0.	0.	0.
Bending coeff:	0.999787	0.998494	0.999181
(ice thickness: 1.5 m)			
Crushing coeff:	0.000408	0.004491	0.001653
Shearing coeff:	0.	0.	0.
Bending coeff:	0.999592	0.995509	0.998347

Model Scale Ice Parameters

Ice compressive strength: 500 kPa
Ice shear strength: 33 kPa
Ice flexural strength: 16.7 kPa

corrections to the measured icebreaking resistance due to variances in model ice properties. It is the development of this strength correction procedure that required the understanding of the ship ice interaction during icebreaking.

As described in Section 3.2, the icebreaking forces are analysed in the present model at ten positions, independently along the bow. The forces analysed from these positions are then averaged to obtain a representative icebreaking force for the specific bow. Figure 3.5 compares the calculated icebreaking forces at various positions for the three bows. Examples of the resultant representative icebreaking forces from the present analysis are shown in Figures 3.6 and 3.7. Figure 3.6 displays the variation of the computed icebreaking forces as a function of the ice flexural and compressive strengths. Figure 3.7 depicts the differences of the forces for the three bows at various ice thickness conditions.

Examination of the calculation results has shown that, within the range of the ice conditions being investigated, the dependence of the icebreaking force, or resistance, on the ice flexural and compressive strengths can be represented reasonably well with the following expression:

$$R \sim (\sigma_f)^A \cdot \left(\frac{\sigma_c}{\sigma_F}\right)^B$$

The exponent of each factor is found to vary with hull form as well as ice thickness. Index 'A' is the exponent of the flexural strength in the icebreaking resistance expression when the compressive strength to flexural strength ratio is a constant. Index 'B' is the exponent of the compressive/flexural strength ratio representing the dependence of the compressive strength on the icebreaking resistance. Index 'A' hereafter in the report is referred to as the flexural strength index, and Index 'B' is referred to as the compressive/flexural strength index.

Using the technique of least square fitting, these indices have been determined from the calculation results and are shown graphically in Figure 3.8. Both indices exhibit a trend relating to ice thickness and hull form. The ARCTIC's old bow exhibits compressive/flexural strength ration index, as compared to those of the other two bows.

Using these indices, the procedure to correct the measured icebreaking resistance for variances in ice strengths is simple. The corrected icebreaking resistance component (R_{corr}) is derived from the measured icebreaking resistance component (R_m) using the following equation:

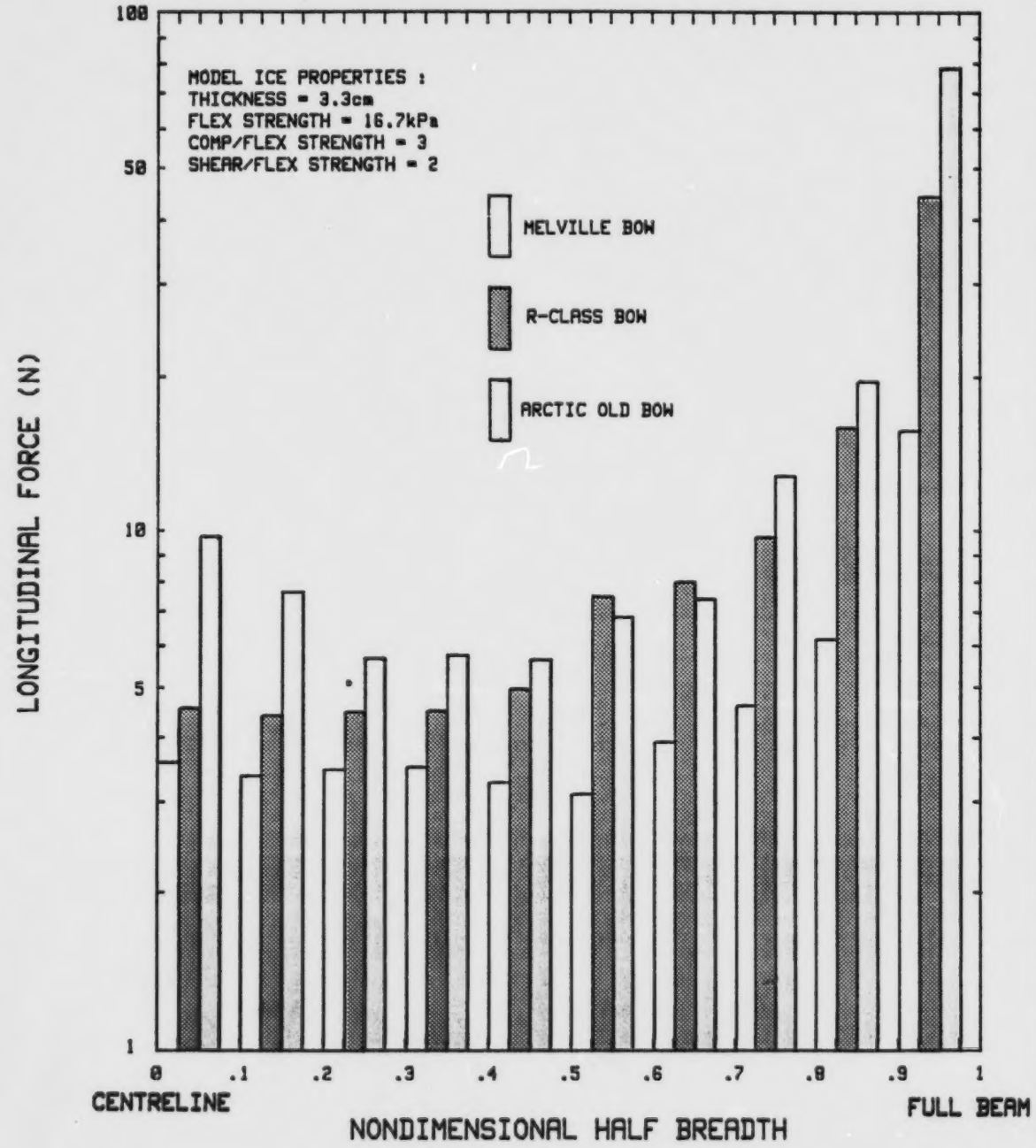
$$\frac{R_{corr}}{R_m} = \left(\frac{\sigma_{F\,(target)}}{\sigma_{F\,(actual)}}\right)^A \left(\frac{\sigma_c/\sigma_{F\,(target)}}{\sigma_c/\sigma_{F\,(actual)}}\right)^B$$

The following example illustrates the full scale performance prediction procedure for the following conditions:

Scale factor: 30
Model ice thickness: 3.3 cm

FIGURE 3.5

CALCULATED LONGITUDINAL ICE FORCES
AT VARIOUS BOW POSITIONS



FORCES IN MODEL SCALE
λ = 30

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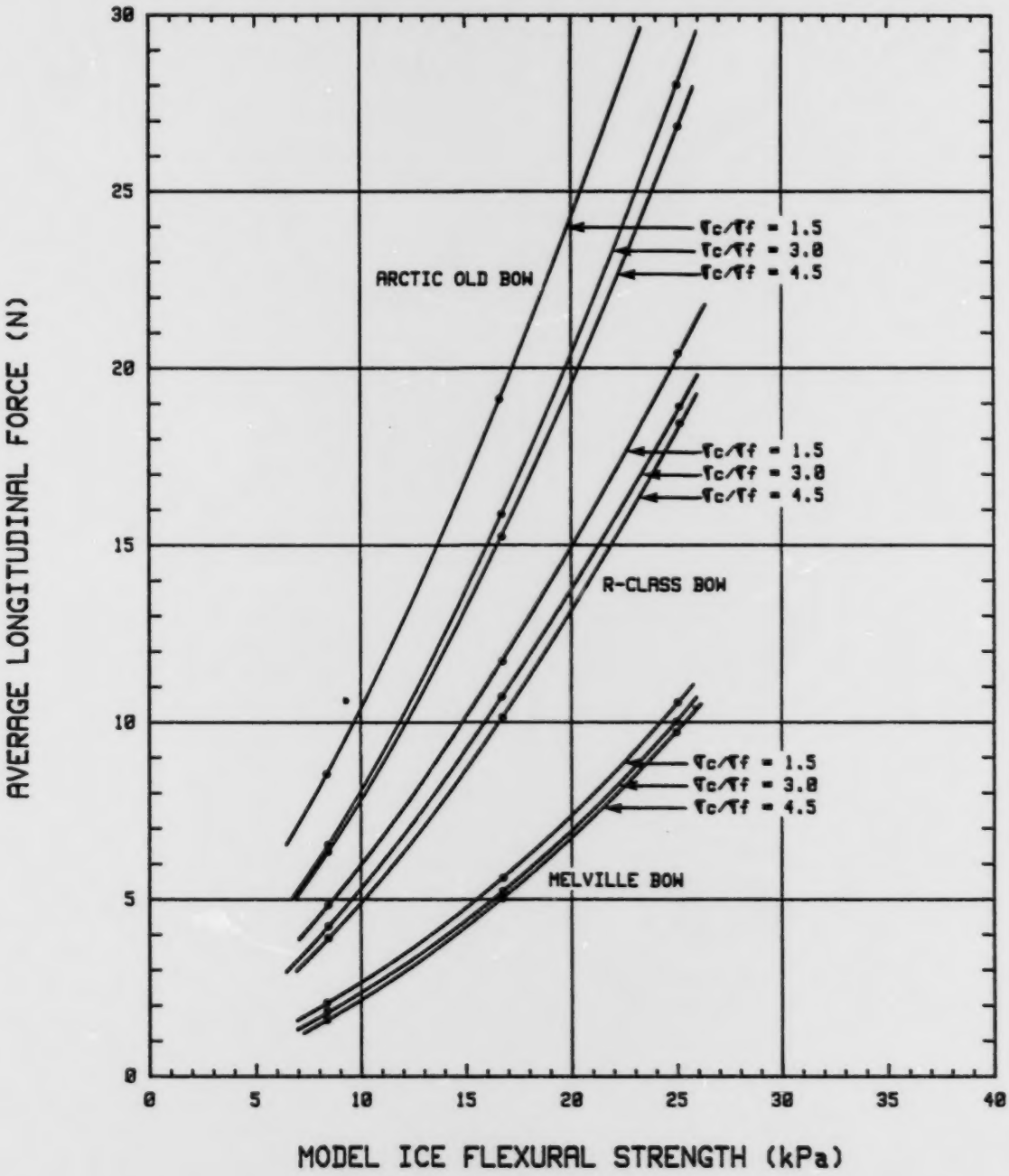
FIGURE 3.6

CALCULATED RESULTANT LONGITUDINAL BOW FORCES FOR VARIOUS ICE STRENGTH CONDITIONS



MODEL SCALE λ = 30
MODEL ICE THICKNESS = 0.033 m

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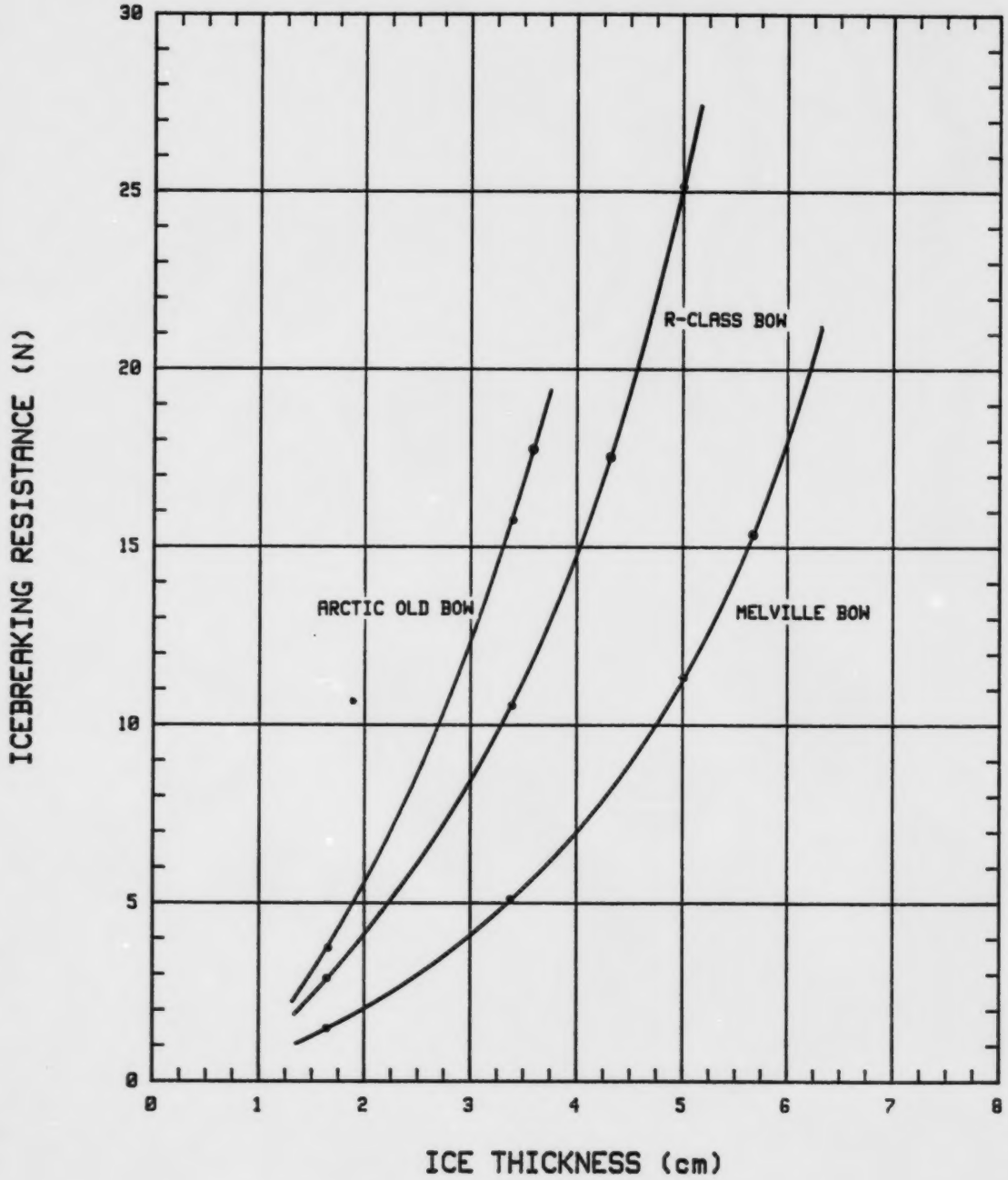
FIGURE 3.7

CALCULATED ICEBREAKING RESISTANCE
VERSUS ICE THICKNESS



τ_f = 16.7kPa
τ_c/τ_f = 3.0
τ_a/τ_f = 2

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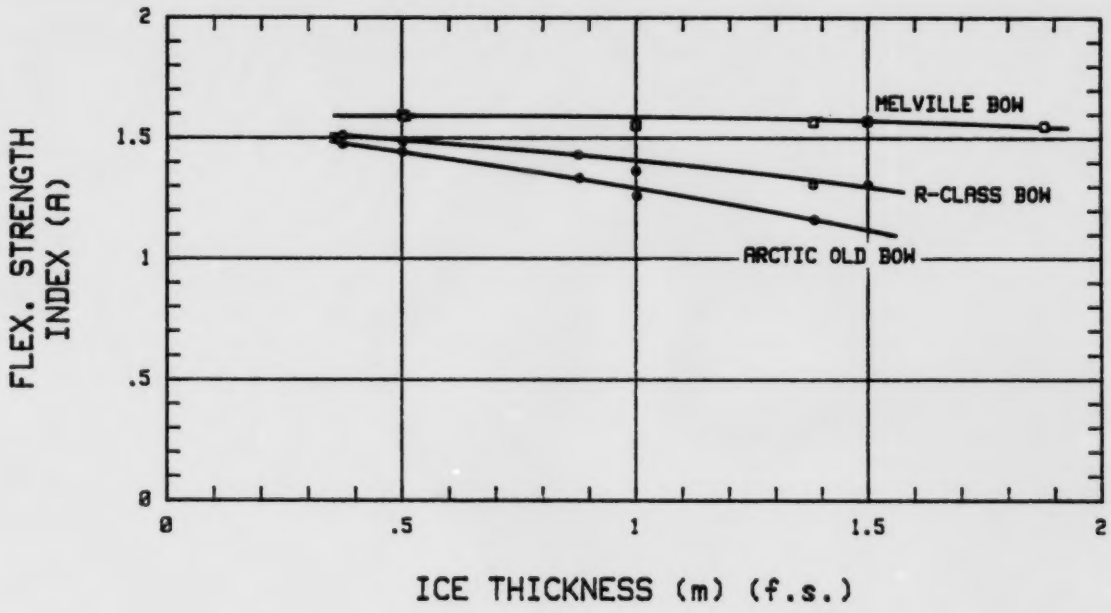
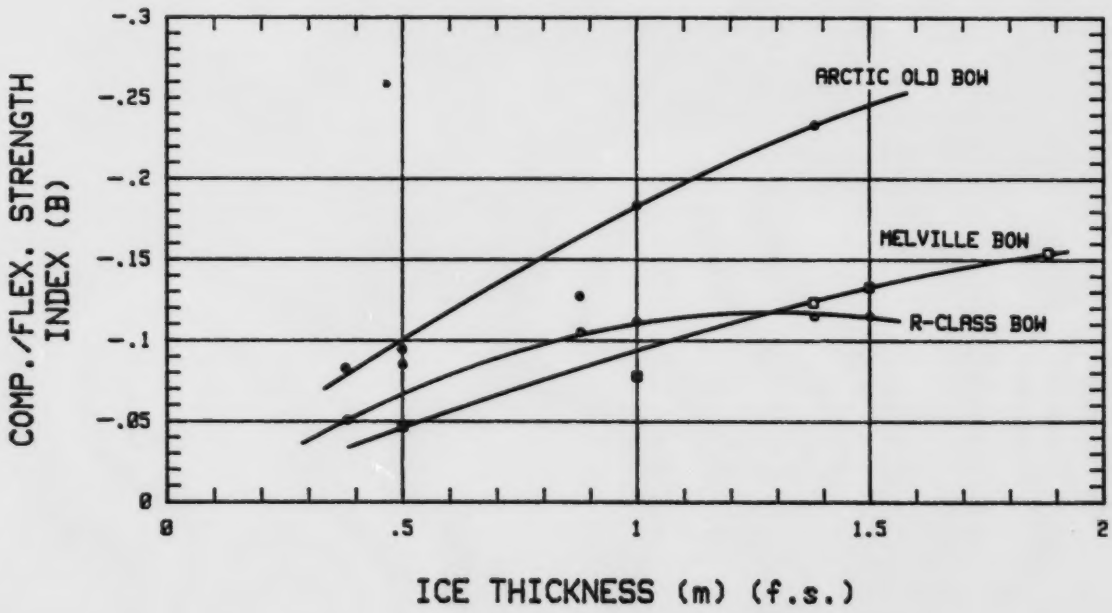
FIGURE 3.8

STRENGTH CORRECTION INDICES





□ MELVILLE BOW
• R-CLASS BOW • OLD ARCTIC BOW

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Model ice flexural strength: 18 kPa
Model ice compressive strength: 40 kPa
Target ice flexural strength in model scale: 20 kPa
Target ice compressive strength in model scale: 50 kPa
Bow type: Melville Bow

Step 1:
- Determine the variance in ice flexural strength.
- Target flex strength/actual flexural strength = 20/18 = 1.11

Step 2:
- Determine the variance in ice compressive/flexural strength ratio.
- Target strength ratio/actual strength ratio (50/20)/(40/18) = 1.126

Step 3:
- Determine the correction factor for the icebreaking resistance.
- From Figure 3.8, the flexural strength index and compressive/flexural strength index for the given ice thickness condition are 1.59 and -0.078, respectively. Using the above equation the correction factor for the icebreaking component of the ship's resistance is therefore,

$$(1.11)^{1.59} \times (1.126)^{-0.095} = 1.17$$

The above example has shown that the icebreaking resistance measured from model tests should be corrected by a factor of 1.17.

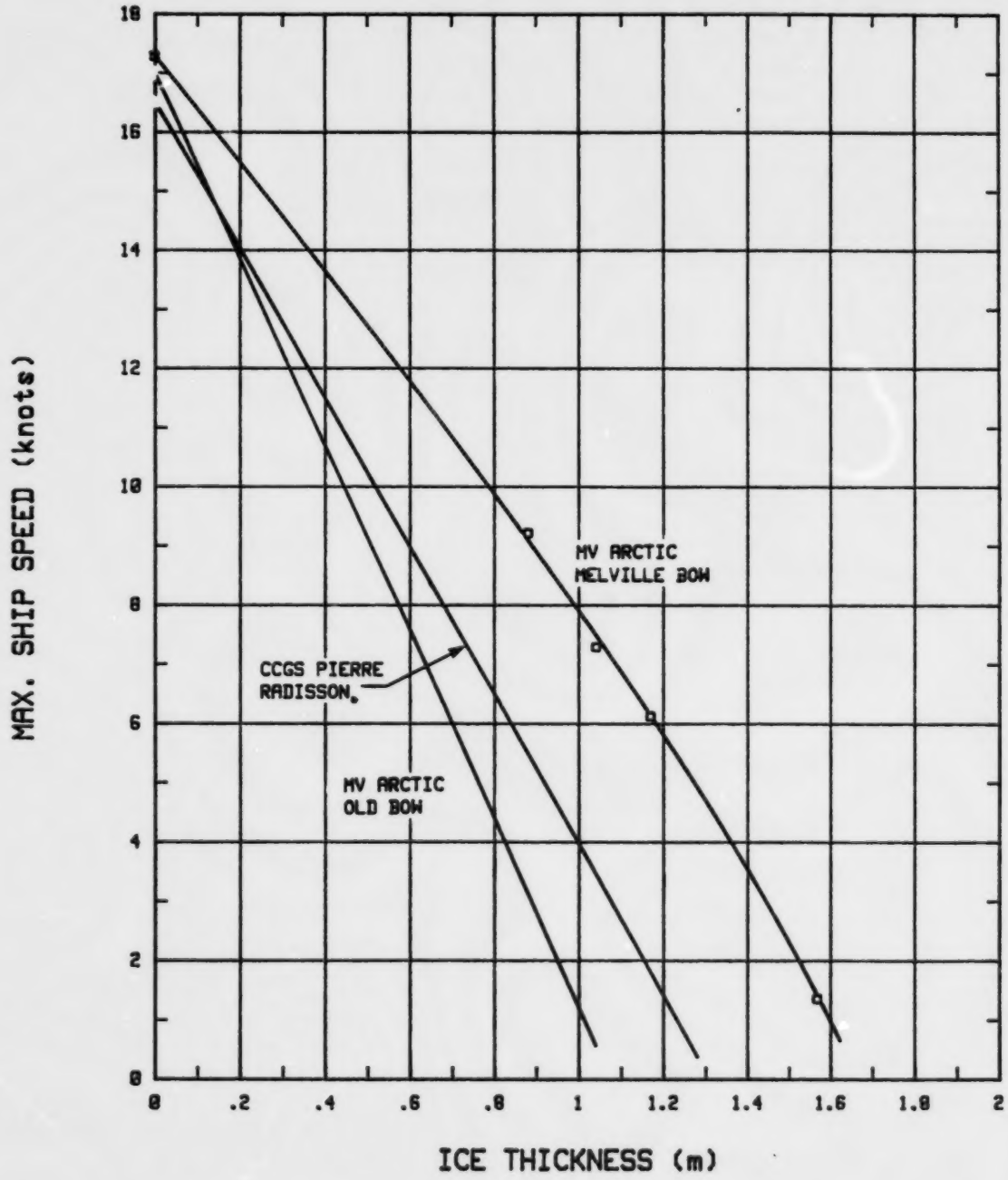
3.5 Discussion

While the present mathematical model has been developed primarily for determining the influence of ice strength and hull form on ship's resistance in ice, it is essential to compare the predicted icebreaking force with the resistance data obtained from full scale measurements. The published full scale test results of R-Class ships are available from those collected by Michailidis and Murdy [5] with the CCGS FRANKLIN and by Edwards [15] with the CCGS PIERRE RADISSON. The performance of the ARCTIC with the old bow was summarised by Albery et al [16], and the full scale test data for the Melville bow is available from Dick and Cheung [17]. Figure 3.9 compares the full scale performance of the three bows by plotting the measured ship speed at full power versus ice thickness. The data shown has been adjusted for 500 kPa flexural strength without snow cover. It should be noted that the full scale data of the R-Class ships is scattered and the curve shown in Figure 3.9 presents the average condition based on the available empirical data.

The comparison between the full scale data and the calculated data can be made by examining the bollard pull of each ship and the calculated icebreaking forces for the maximum ice thickness the ships can break, i.e. at full power and creeping speed conditions. The maximum ice thickness for the ARCTIC with the old bow was about 1.1 m, and the maximum ice thickness for the R-Class ship and the ARCTIC fitted with the Melville bow are about 1.3 and 1.7 m respectively.

FIGURE 3.9

FULLSCALE PERFORMANCE
SPEED VERSUS ICE THICKNESS



- NO SNOW
- FLEXURAL STRENGTH 500 kPa

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	Ice Thickness (m)	Bollard Pull (kN)	Calculated Icebreaking Force (kN)	Calculated Force/Bollard Pull Ratio	Ref.
Melville Bow	1.7	1,520	416	0.27	[17]
R-Class Bow	1.3	1,505*	475	0.32	[5, 15]
ARCTIC Old Bow	1.1	1,520	486	0.32	[16]

* The bollard pull of the R-Class bow shown above has been adjusted for the same breadth as the M.V. ARCTIC.

The calculated average longitudinal icebreaking forces of these three selected bows are found to be about 27 to 32 percent of the total resistance or bollard pull of the ships.

Based on a series of full scale presawn ice experiments, Enkvist [9] has shown that a ship with a beam of 22.9 m, such as the M.V. ARCTIC, may have an icebreaking resistance component of about 40 to 70 percent of the total resistance of the ship when operating at creeping speed. This implies that the present mathematical model has only indicated about 50 percent of the total icebreaking resistance. The remaining portion of the icebreaking resistance is likely due to many factors which have not been considered in the analysis. One of the factors which can have a strong dependence on hull form is ice friction. It is clear that the existence of friction may effect the mechanisms of icebreaking. For example, by taking the Coulomb Law, the vertical bow force can be substantially retarded if the hull flare angle is about or less than the friction angle, which in turn will favor an ice crushing mechanism rather than bending. The friction forces therefore should be considered in any development of this icebreaking mechanisms analysis.

As described in Section 3.3, the hull form coefficients have been defined with the intention of quantifying the effectiveness of a given hull form design and to evaluate the icebreaking mechanisms of a bow in terms of the different failure modes. The coefficients have been defined by a measure of the ice volumes which have been crushed, sheared or bent by the hull. The hull form coefficients thus defined have not been used directly in this stage to derive the strength correction factors for full scale performance prediction. However, the coefficients have proved to be an important gauge for depicting the quality and the validity of the assumptions used in the analysis and for forecasting the icebreaking performance of a specific bow design.

At present there appears to be no available published ice failure condition data which can be used to compare directly with the computed hull form coefficients.

The present calculations have been made for an independent variation of ice flexural strength or compressive strength using a constant ice

elastic modulus. The result has shown that the icebreaking forces are proportional to the flexural strength to the power of about 1.1 to 1.6 and proportional to the compressive strength/flexural strength ratio to the power of about 0.05 to 0.25 (see Figure 3.8). The deduced ice strength indices are found to vary with hull form and ice thickness.

It has been shown by Enkvist [6] that the dependence of the ice-breaking force to ice flexural strength and elastic modulus may be approximated by:

$$R \quad \left(\frac{\sqrt{\sigma_F}}{E}\right) \cdot \sqrt{\sigma_f}$$

This gives a flexural strength index of two: the difference reflects the approaches used in the calculations.

It is generally accepted that the ice elastic modulus to flexural strength ratio for either model ice or sea ice can vary significantly, typically 2,000 to 8,000 for sea ice and 1,000 to 3,000 for model ice. Because of the uncertainty of this parameter, it is obvious that the correction of the ice resistance from model testing can be made meaningfull only if the elasticity properties of the model ice are known and the target condition is well defined.

When the elastic modulus varies linearly with flexural strength it is expected that, for example by following the Enkvist equation, the resulting flexural strength index will become about one. However, when the elastic modulus varies non-linearly or inconsistently with ice strength, then a completely different relationship may result between the ice resistance and the ice strength. This is manifested by the results of the strength indices obtained empirically from model test data.

Ice Tank	Ice Type	Flex Strength (exponent)	Reference
CRREL	UREA	1.70	Tatinclaux (1984)
IMD	EG/AD/S	1.00	Spencer (1987)
ARCTEC INC.	SALINE	.25	Lecourt (1975)
WIMB	HIGH SALINE	.65	Roos et al (1976)

In summary, it is identified that the friction between ice and hull, and the elastic properties of the ice cannot be neglected in the consideration of hull form coefficients and the development of the strength correction procedure. The next stage of the research work on performance should focus on these two problem areas.

4. CONCLUSIONS

This phase of Indexer development has been completed in two parts. The conclusions for each part of the project may be defined as:

Part I: Indexer Design Optimisation

- The overall performance of the redesigned Indexer was very promising and indicated, that this equipment, if developed further, has the potential to become a standard piece of testing apparatus for model ice tanks wishing to monitor the relative flexural shear and crushing strength of the ice sheet.

- The results from the Indexer, tested in the ice sheets on an opportunity basis, showed similar trends to the results from the manual measurement technique.

- The accuracy of manual ice testing techniques have been observed to be questionable with specific reference to the shearing and crushing failure modes.

- The manual tests for shear and crushing strengths were not suitable to calibrate the shear and crushing plates of the Indexer due to problems experienced with the test equipment.

Part II: Development of Full Scale Prediction Technique

- It has been demonstrated that the simulation model approach for the analysis of the ice strength and hull form has the potential to provide a powerful tool to the Arctic ship designer. Further development of the model is necessary to improve the code and assess the basic assumptions.

- A prototype system has been developed to evaluate the effect of strength on resistance for a particular hull form. This system indicates that the ice flexural strength and compressive strength influences the ice resistance differently for different hull forms. As a result, a correction of the measured resistance from model tests is necessary when the target full scale ice strength properties are not correctly scaled.

5. RECOMMENDATIONS

There are a number of recommendations that have resulted from this research work. These may be summarised by:

Part I: Indexer Design Optimisation

- The Indexer design and operation should be developed further. This should include providing a fixed and steady platform for the device closer to the model, together with a review of the plate orientation, load cells and ice cutting method.

- The manual techniques, needed for comparison to full scale values, must be developed to permit a more accurate assessment of the crushing and shearing ice properties.

- The Indexer should be re-tested with dedicated ice sheets.

Part II: Development of Full Scale Prediction Technique

- The performance prediction procedure should be tested and refined with the model and full scale test data for various hull forms.

- The mechanisms of the icebreaking process should be analysed further. A more rigorous and precise descriptive method of the ship/ice interaction should be developed to eliminate, progressively, the assumptions which have been used in the present model.

- The analysis technique should be generalised to extend its application to a variety of hull forms, including non-conventional bow forms.

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M.V. ARCTIC Ship Performance Testing, Spring 1986. Canarctic Shipping Company Limited. 1986

APPENDIX 1

CALCULATION OF ICE STRENGTH INDEX

The forces applied on the Indexer's bending, shearing and crushing plates are recorded from each run of the Indexer. This data, coupled with the record of towing carriage speed, allows a definition of the ice's flexural, shear and compressive strength properties along the ice tank. The ice strength information is extracted from the peaks in the force spectra which are associated with the incidents of ice failure during the operation of the Indexer.

The computer programme has been developed to extract the ice strength information automatically from the Indexer output data and present the results graphically in various formats.

The flexural strength data is derived from the standard cantilever beam formulation with a correction factor to compensate for the angle of the bending plate. The length of each ice beam is computed from the time difference between the corresponding peaks in the force spectrum.

The shear strength is determined from the measured peak shear force and the corresponding shear area. Similar to the approach used for the flexural strength, the time difference between peaks is utilised to determine the length of the ice sheared by the Indexer's shear plate. The shear line is assumed to be a straight line parallel to the direction of the Indexer's motion.

The compressive strength is determined from each individual peak in the crushing force output and is assumed to be normal to the crushing plate. The measured peak load is corrected for the angle between the plate and the load cell.

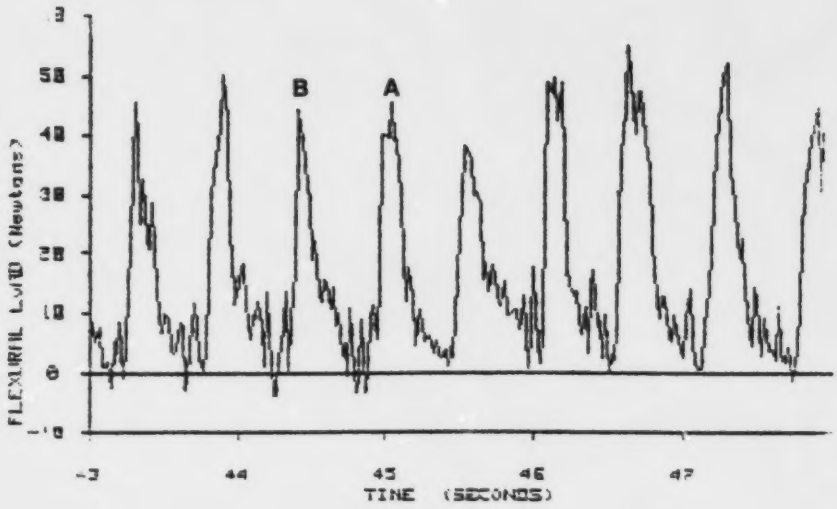
A summary of the equations used for calculating the ice strengths from the measured data are given below.

Flexural Strength

The flexural strength of the ice corresponding to the peak position 'A' in the flexural force diagram is derived from:

$$\overline{V}_f = \frac{6 F_f L_f \cos\Theta_f}{h^2 W_f}$$

where
- $\overline{V}_f$: ice flexural strength
- F_f : measured peak bending force at position 'A'
- h : ice thickness at position 'A'
- W_f : horizontal width of the bending plate
- Θ_f : angle of the bending plate to the horizontal
- L_f : distance between peaks 'A' and 'B'

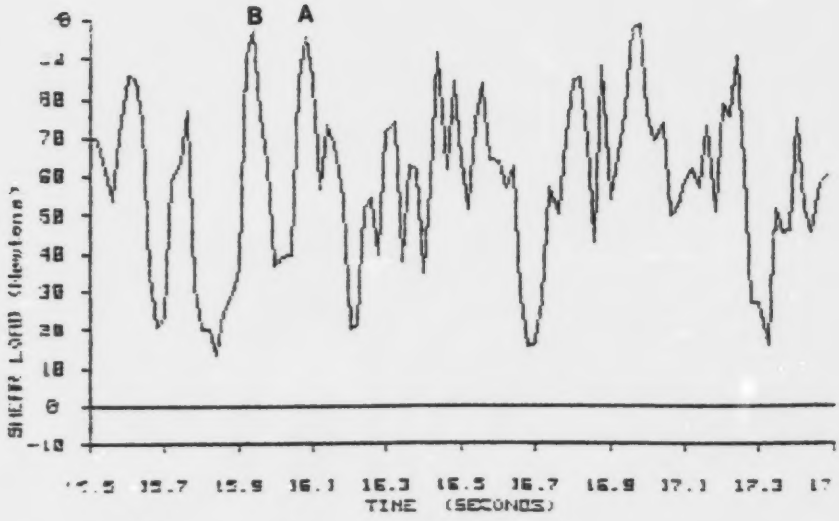


Shear Strength

The shear strength of the ice corresponding to the peak position 'A' in the above diagram is derived from:

$$\bar{V}_s = \frac{F_s \cos \Theta_s}{h L_s}$$

where
- $\bar{V}_s$: ice shear strength
- F_s : measured peak shear force at position 'A'
- h : ice thickness at position 'A'
- Θ_s : angle of the shear plate
- L_s : distance between peaks 'A' and 'B'

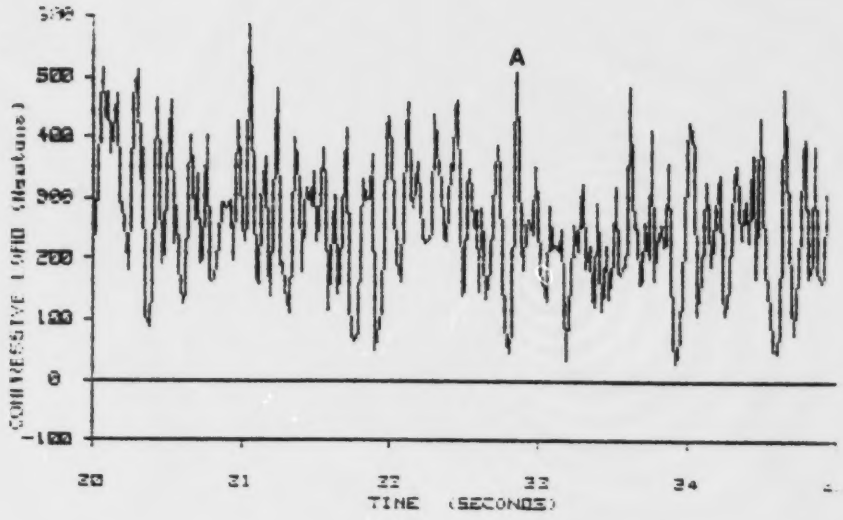


Compressive Strength

The compressive strength of the ice corresponding to the peak position 'A' in the above crushing force diagram is derived by

$$\overline{\sigma}_c = \frac{F_c}{\cos\theta_c \, h \, W_c}$$

where
- $\overline{\sigma}_c$: ice compressive strength
- F_c : measured peak crushing force at position 'A'
- h : ice thickness at position 'A'
- W_c : horizontal width of the crushing plate
- θ_c : angle of the crushing plate



APPENDIX 2

DATA SHEETS FROM INDEXER TESTS

This appendix presents the results of the initial tests of the Indexer at IMD during August to October 1987. The data is plotted as a function of the tank position, including the measured ice force and the deduced ice strength from the Indexer output, and the manually measured ice thickness and strength data. A list of figures of the appendix is given below.

RUNS		FLEX.STRENGTH	SHEAR STRENGTH	COMP.STREGNTH
4-Aug.-1987	09:51:46	Figure A2.1	Figure A2.18	Figure A2.35
	09:55:39	Figure A2.2	Figure A2.19	Figure A2.36
	11:54:53	Figure A2.3	Figure A2.20	Figure A2.37
	14:32:14	Figure A2.4	Figure A2.21	Figure A2.38
	14:36:04	Figure A2.5	Figure A2.22	Figure A2.39
	16:00:53	Figure A2.6	Figure A2.23	Figure A2.40
7-Aug.-1987	13:35:29	Figure A2.7	Figure A2.24	Figure A2.41
	13:45:49	Figure A2.8	Figure A2.25	Figure A2.42
	15:42:47	Figure A2.9	Figure A2.26	Figure A2.43
	16:34:48	Figure A2.10	Figure A2.27	Figure A2.44
15-Sept-1987	12:33:15	Figure A2.11	Figure A2.28	Figure A2.45
16-Sept-1987	17:04:34	Figure A2.12	Figure A2.29	Figure A2.46
17-Sept-1987	13:18:06	Figure A2.13	Figure A2.30	Figure A2.47
22-Sept-1987	12:00:19	Figure A2.14	Figure A2.31	Figure A2.48
24-Sept-1987	15:16:46	Figure A2.15	Figure A2.32	Figure A2.49
6-Oct.-1987	18:03:03	Figure A2.16	Figure A2.33	Figure A2.50
8-Oct.-1987	16:59:26	Figure A2.17	Figure A2.34	Figure A2.51

FIGURE A2.1

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 4-AUG-1987 09:51:46

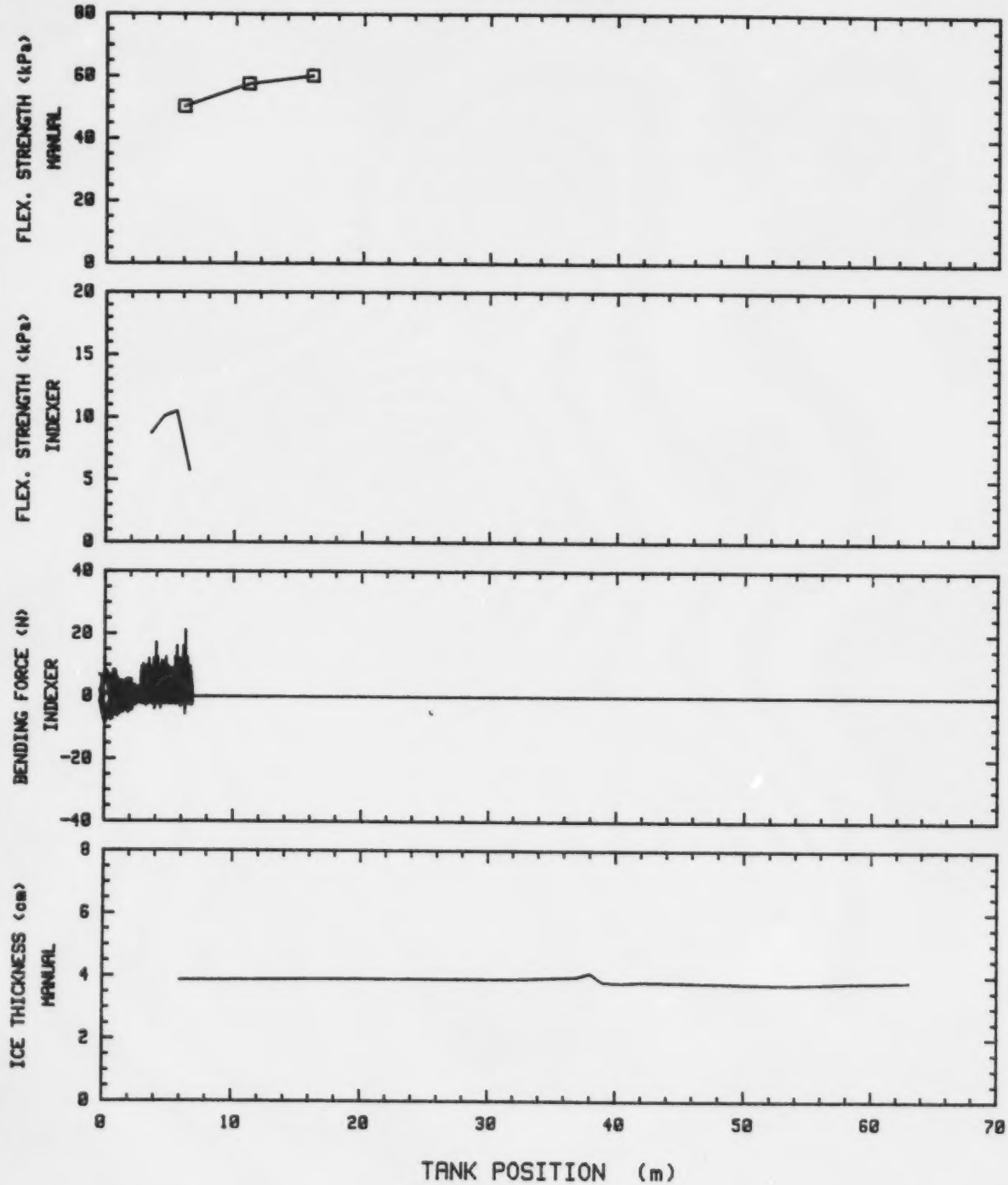


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FIGURE A2.2

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 4-AUG-1987 09:55:39

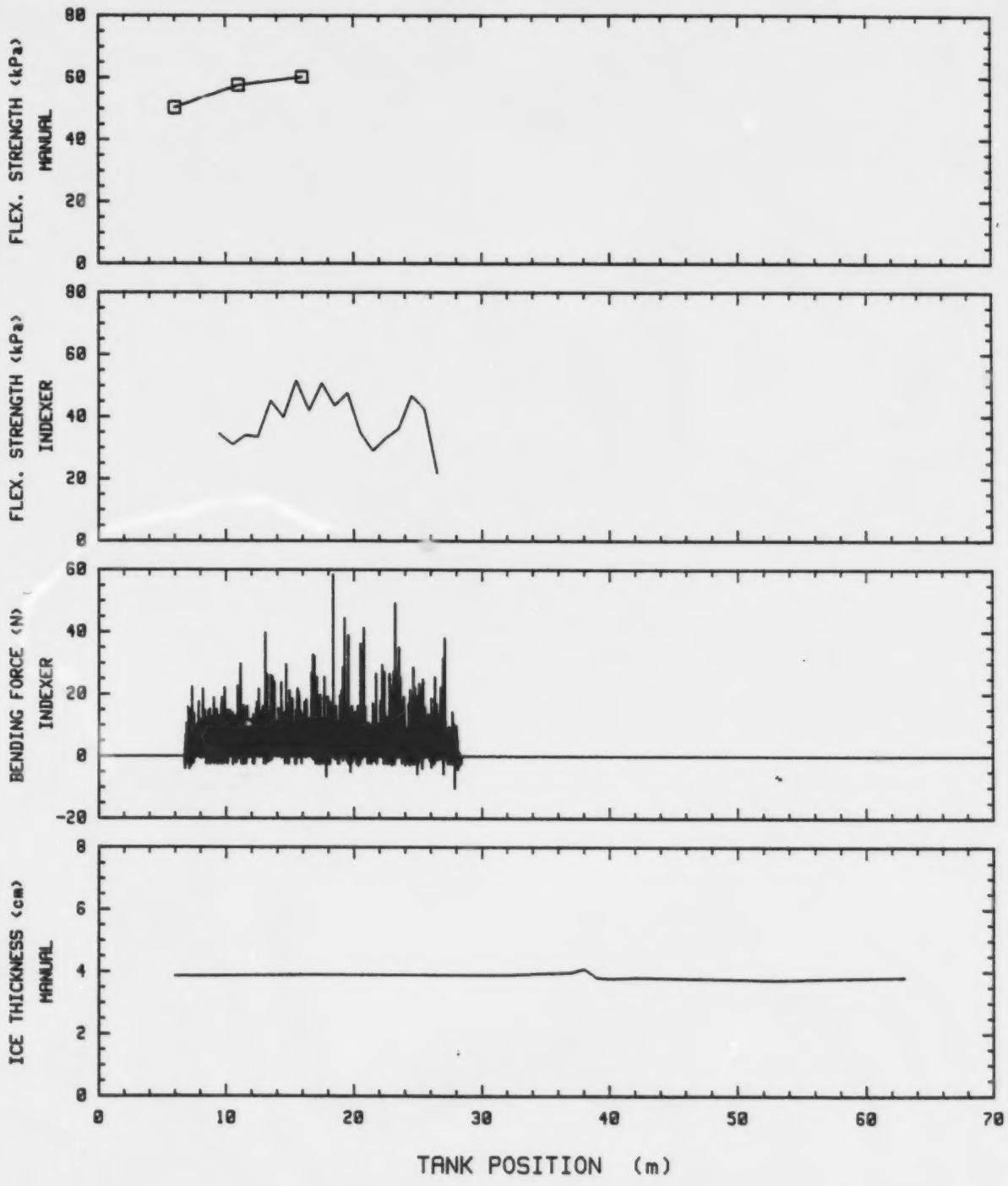

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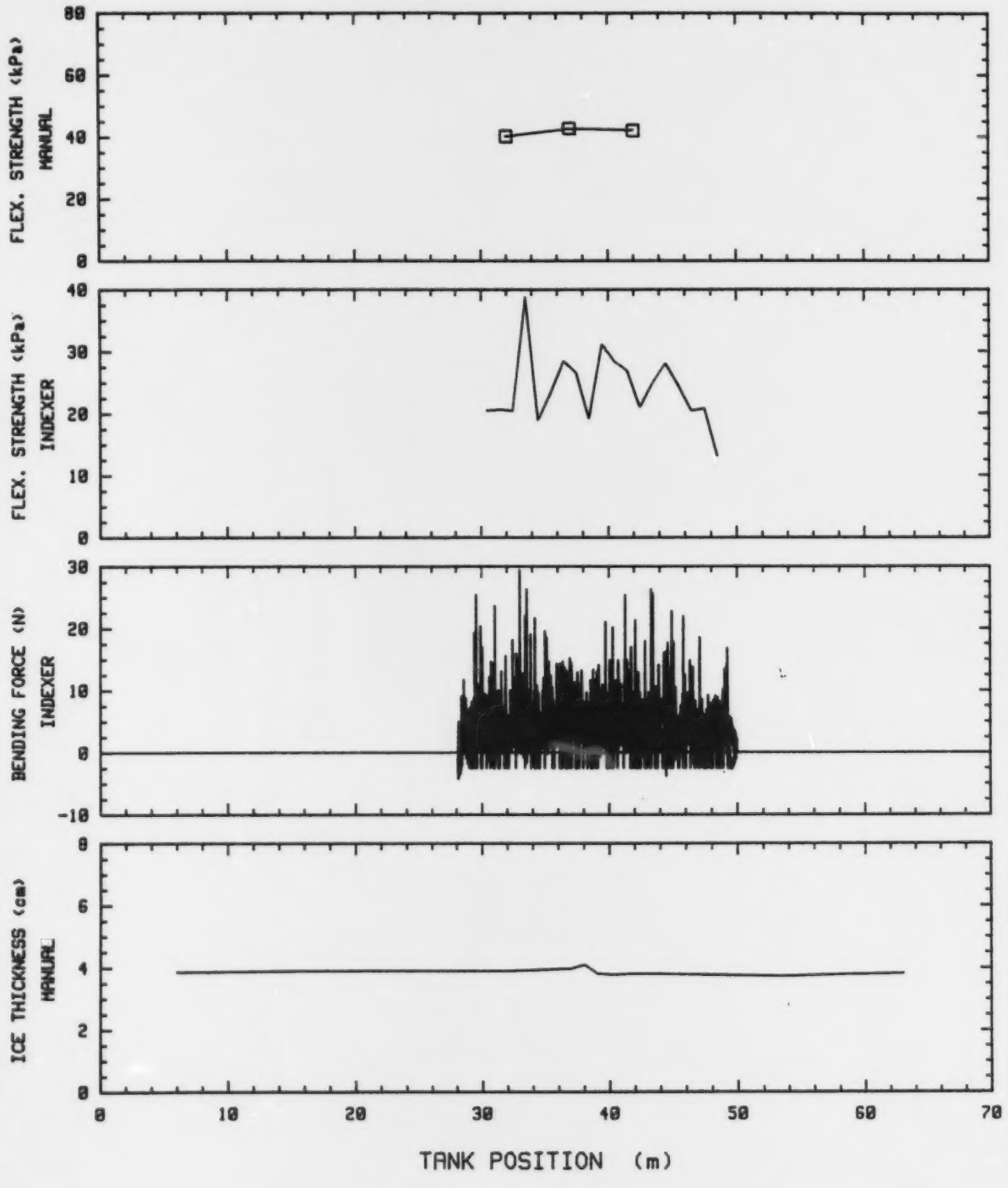
FIGURE A2.3

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 4-AUG-1987 11:54:53

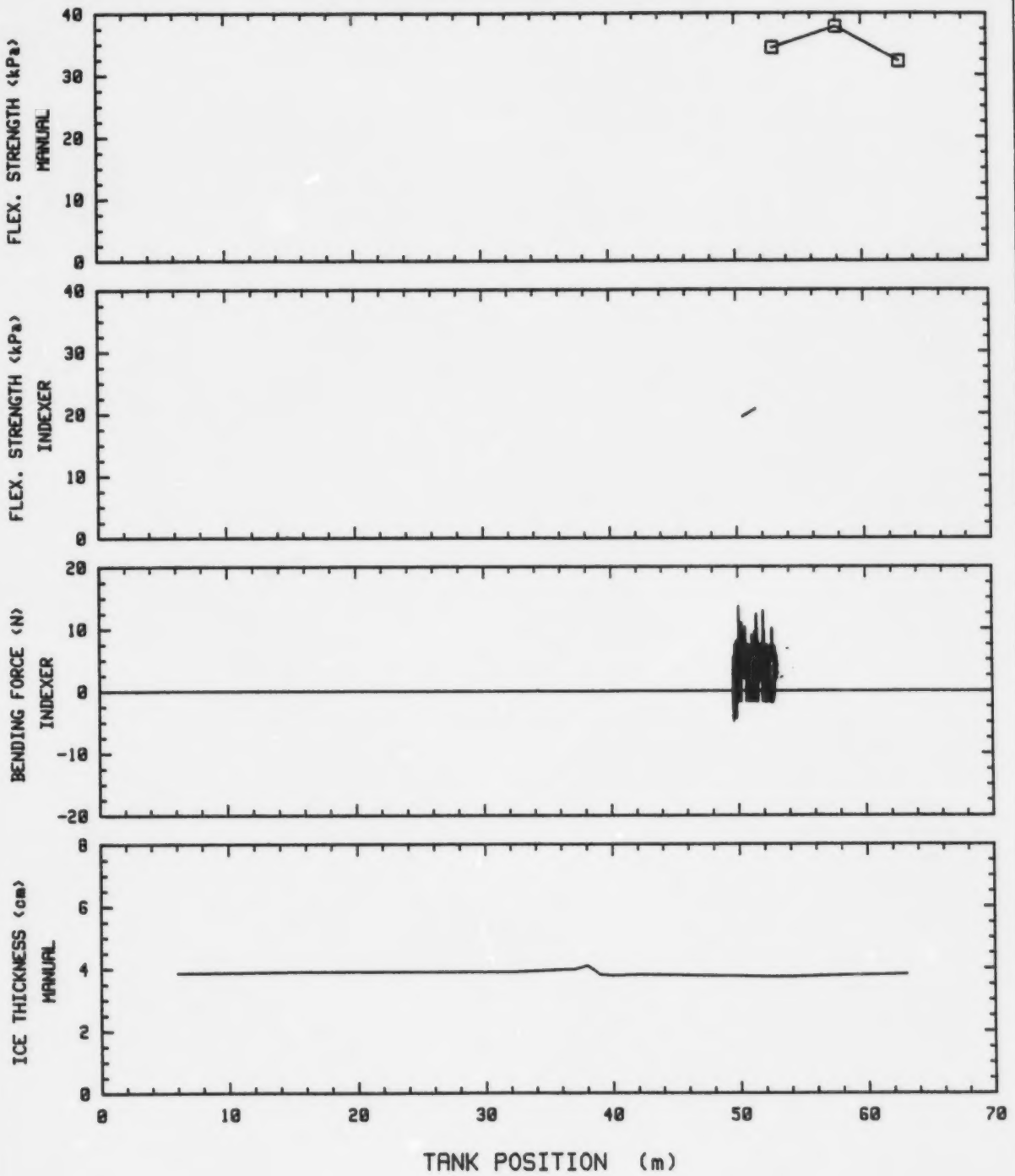


MELVILLE SHIPPING LTD

FIGURE A2.4

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 4-AUG-1987 14:32:14

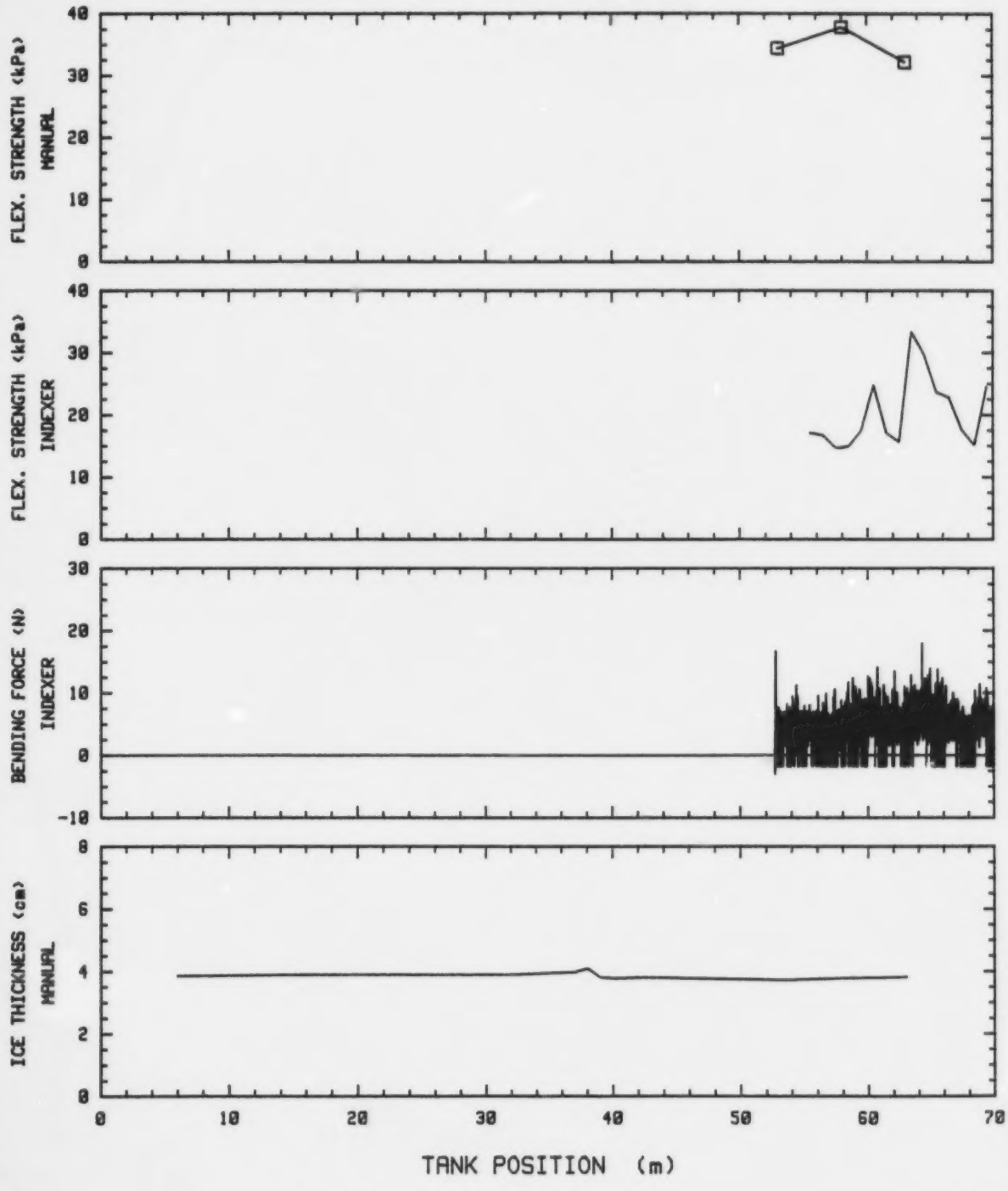


MELVILLE SHIPPING LTD

FIGURE A 2.5

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 4-AUG-1987 14:36:04

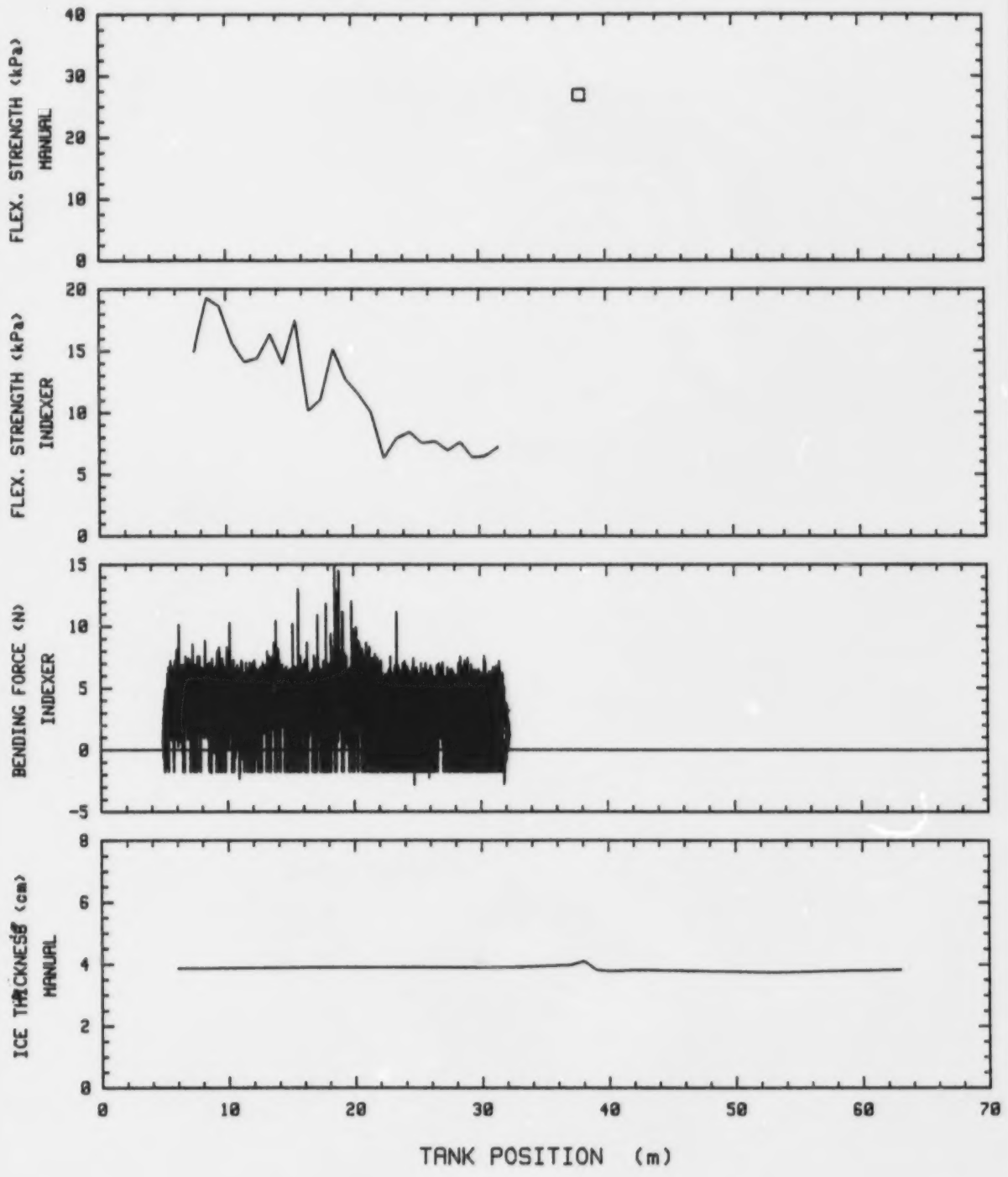


MELVILLE SHIPPING LTD

FIGURE A2.6

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 4-AUG-1987 16:00:53

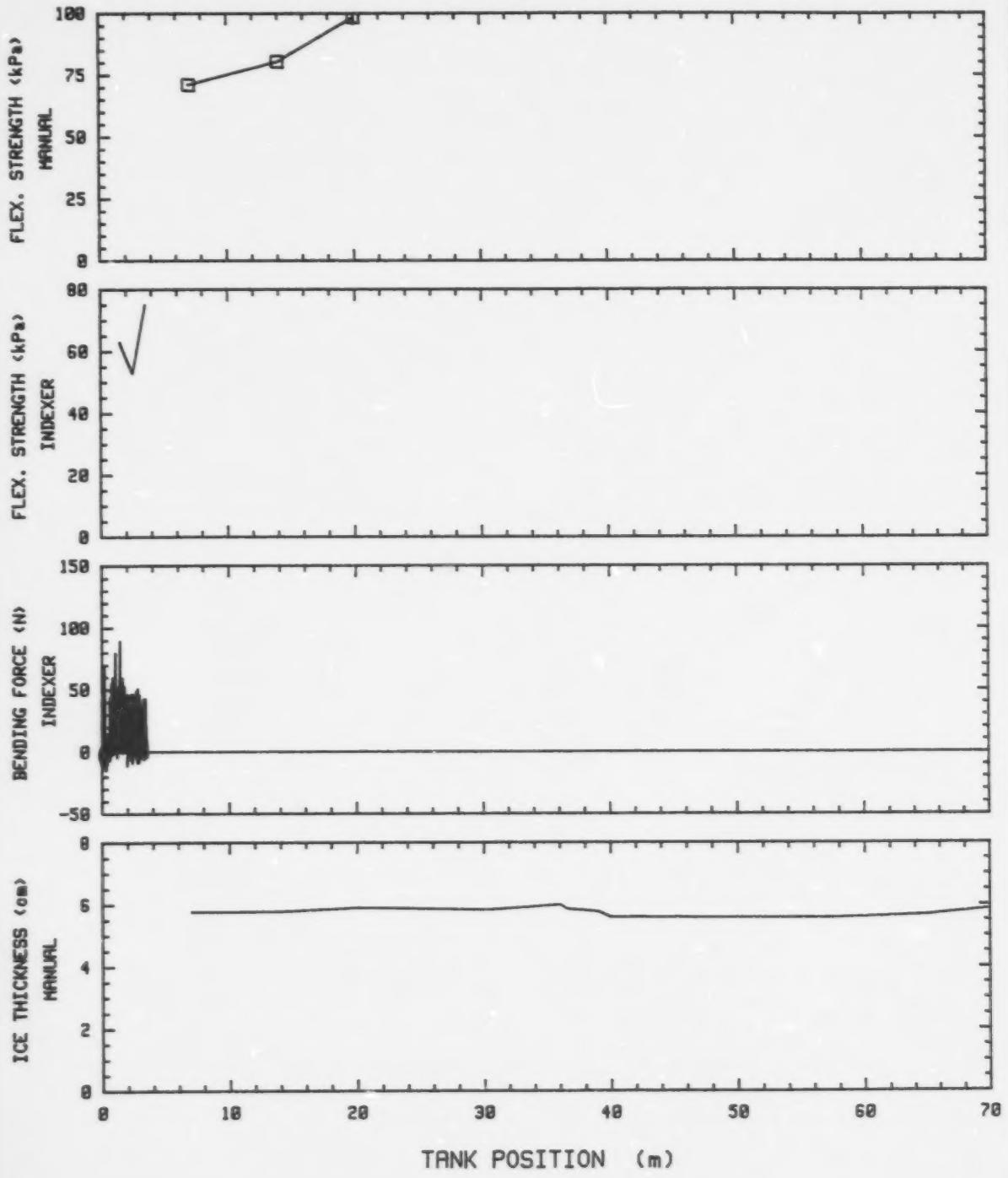


MELVILLE SHIPPING LTD

FIGURE A2.7

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 7-AUG-1987 13:35:29

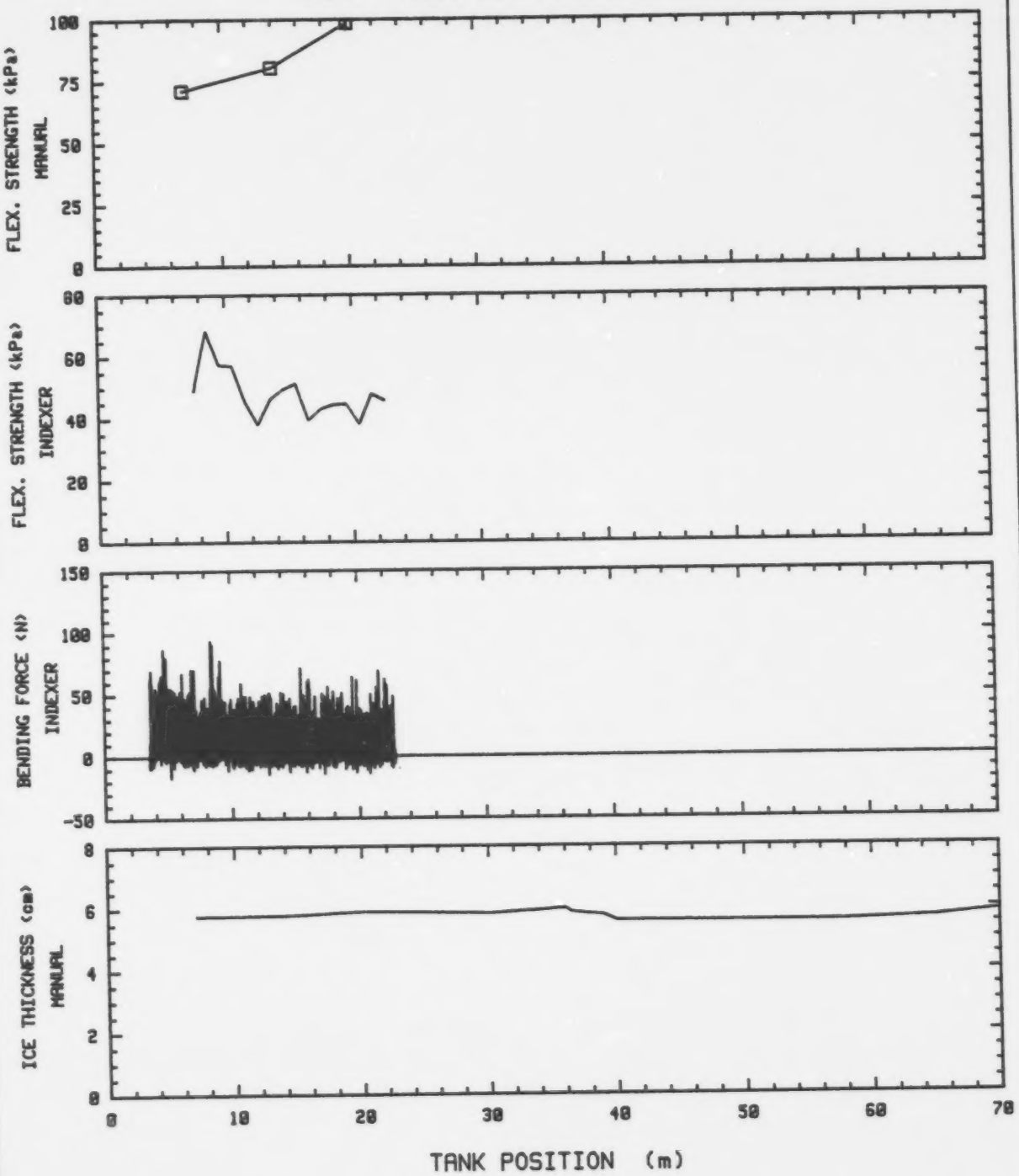


MELVILLE SHIPPING LTD

FIGURE A2.8

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 7-AUG-1987 13:45:49

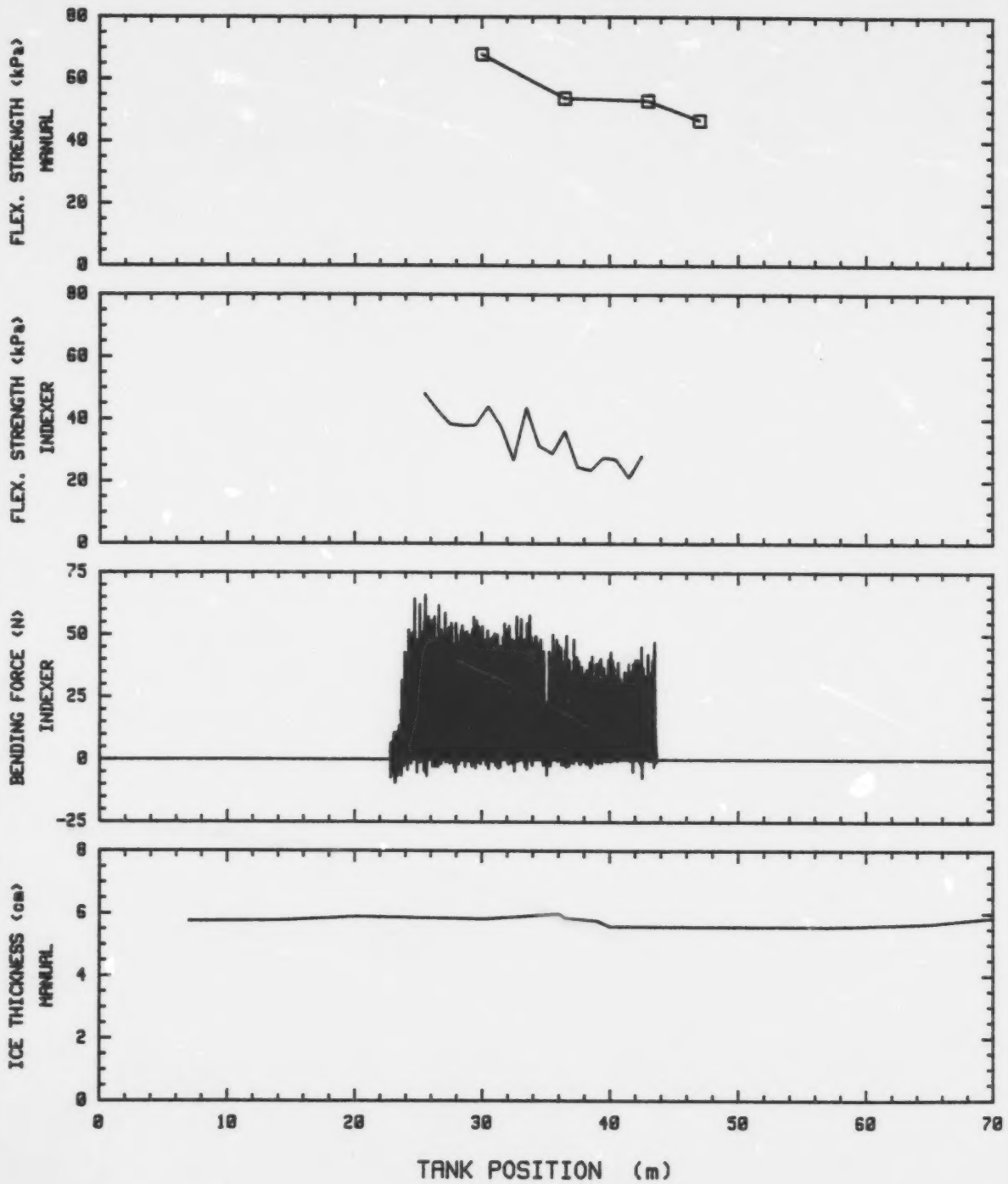


MELVILLE SHIPPING LTD

FIGURE A2.9

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 7-AUG-1987 15:42:47

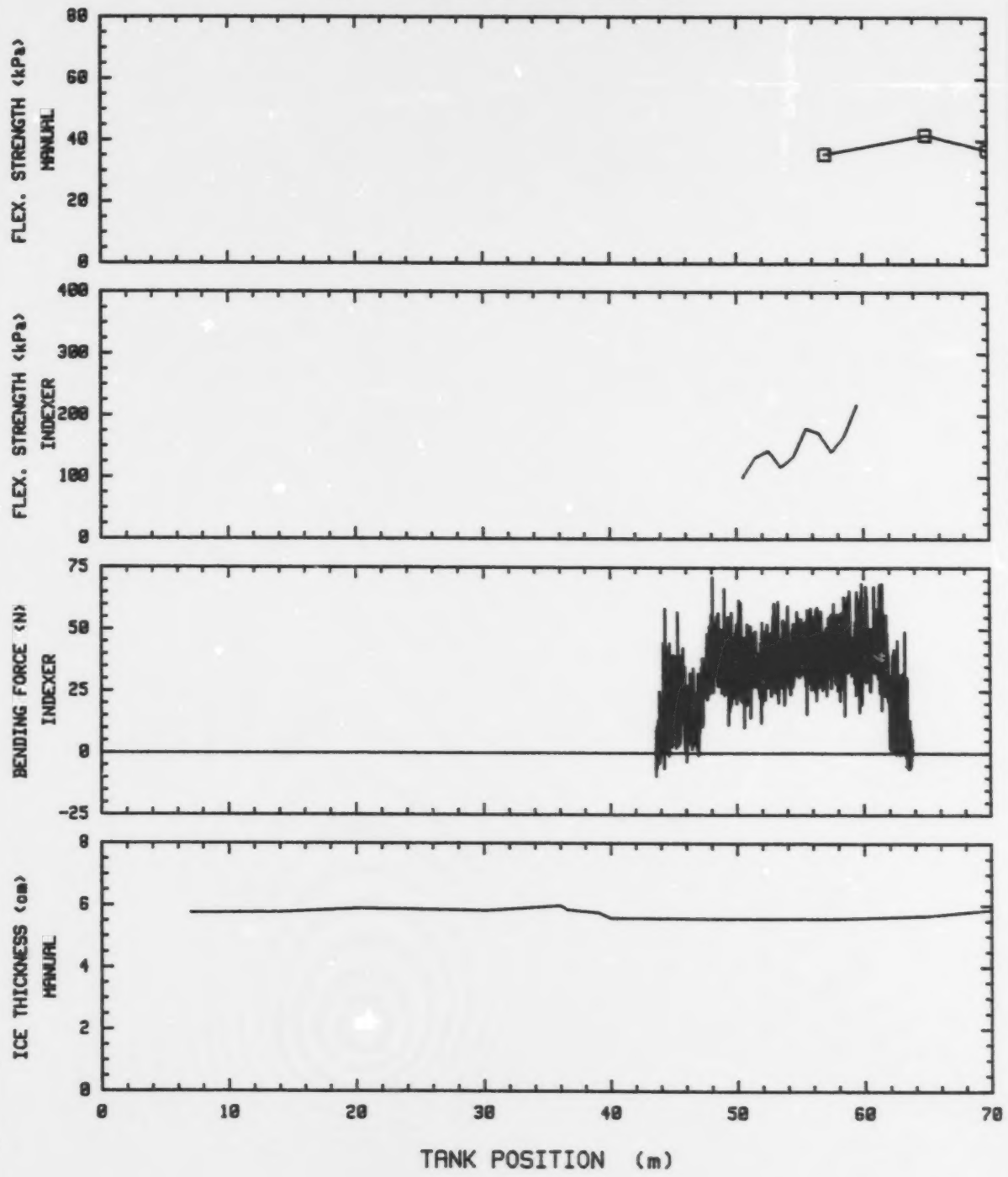


MELVILLE SHIPPING LTD

FIGURE A2.10

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 7-AUG-1987 16:34:48

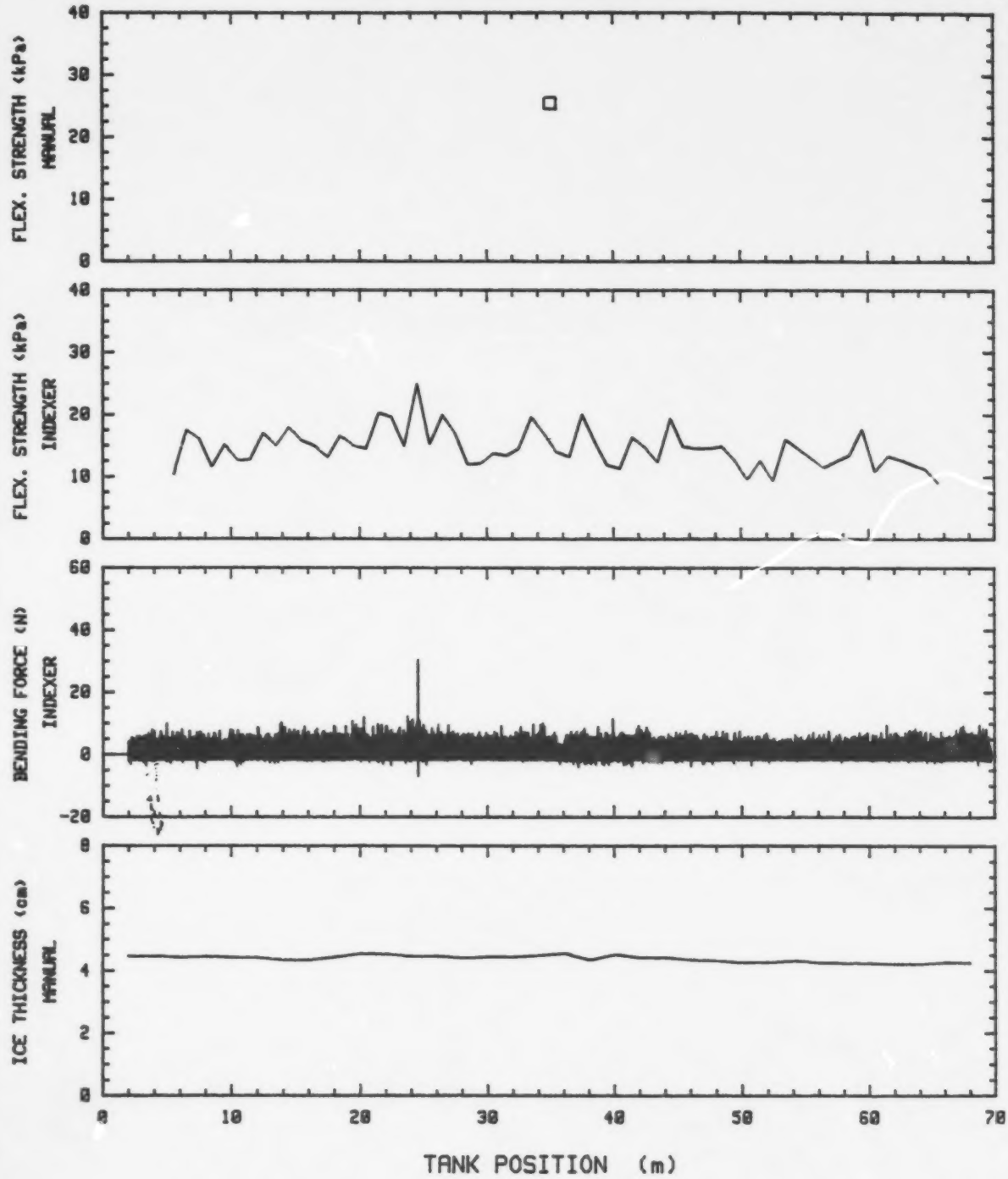


MELVILLE SHIPPING LTD

FIGURE A2.11

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 15-SEP-1987 12:33:15

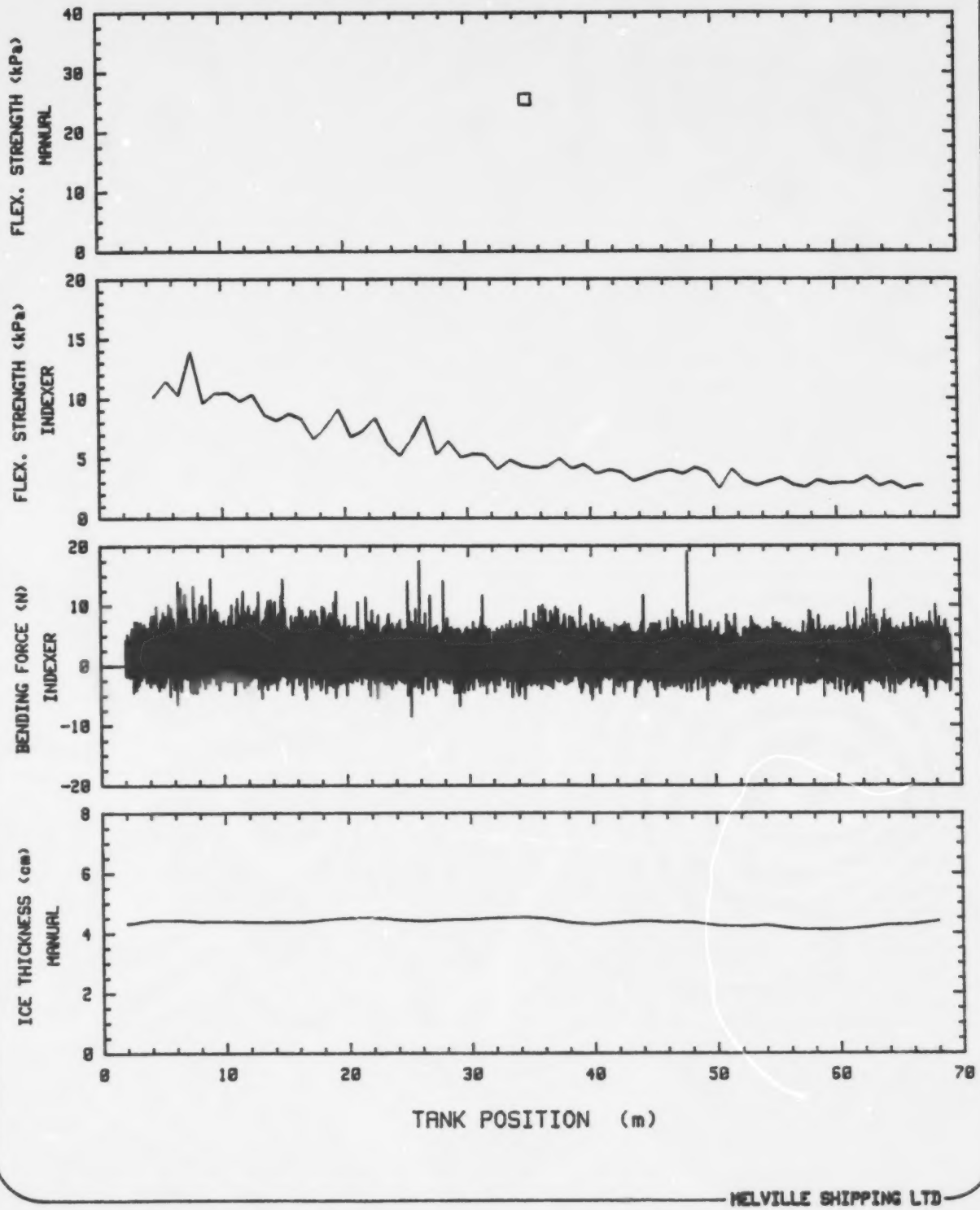


MELVILLE SHIPPING LTD

FIGURE A 2.12

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 16-SEP-1987 17:04:34

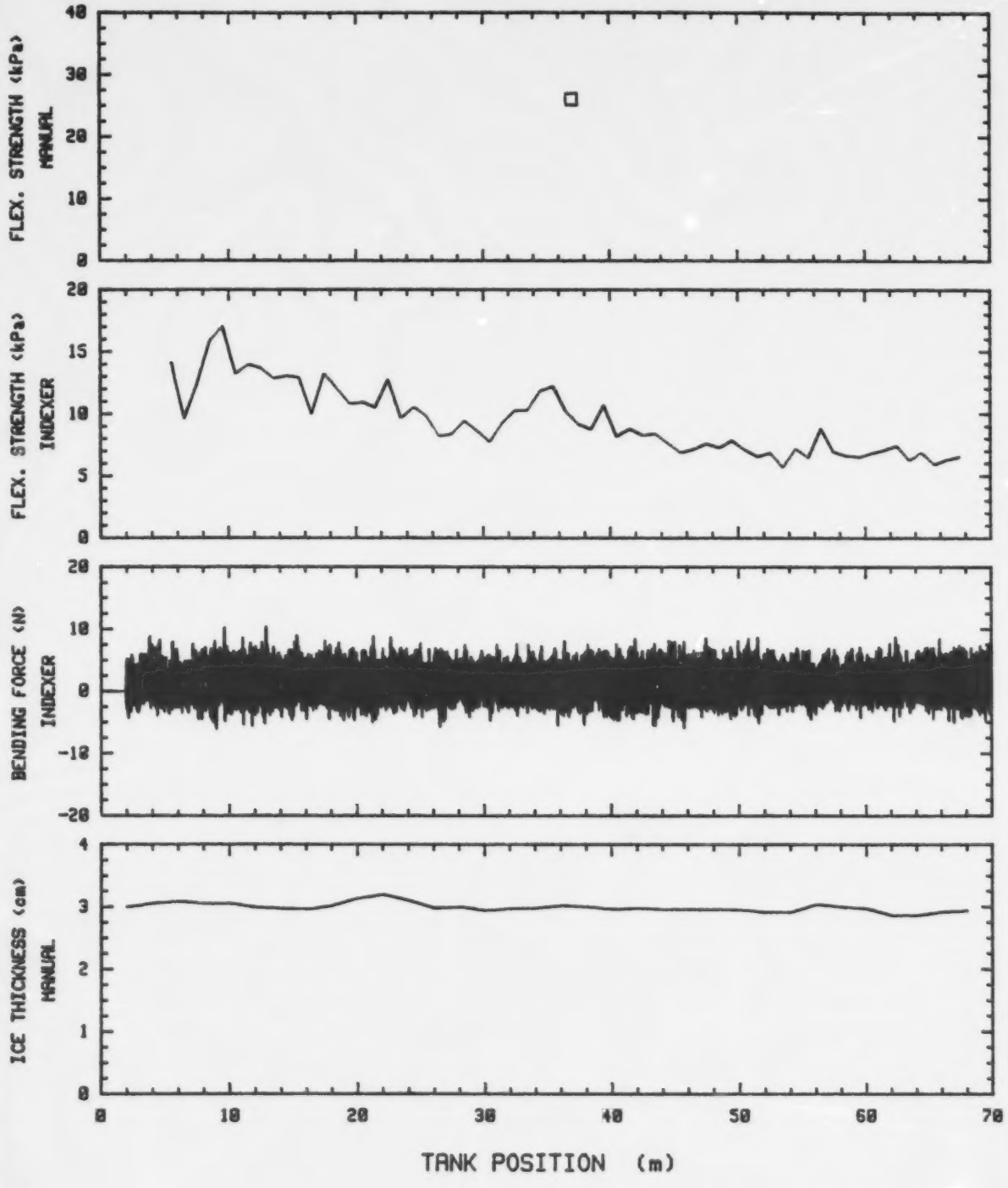


MELVILLE SHIPPING LTD

FIGURE A2.13

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 17-SEP-1987 13:18:06

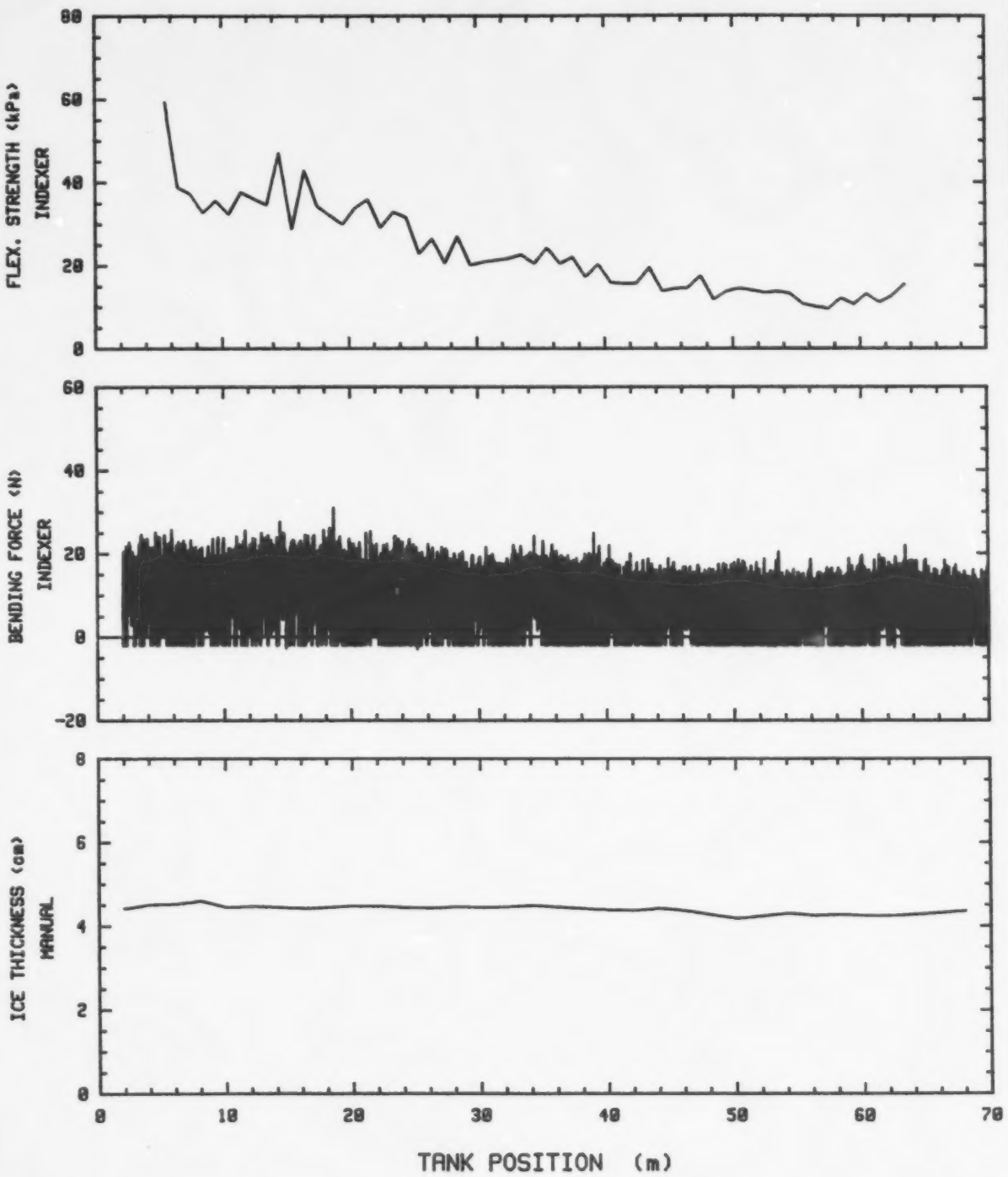


MELVILLE SHIPPING LTD

FIGURE A 2.14

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 22-SEP-1987 12:00:19

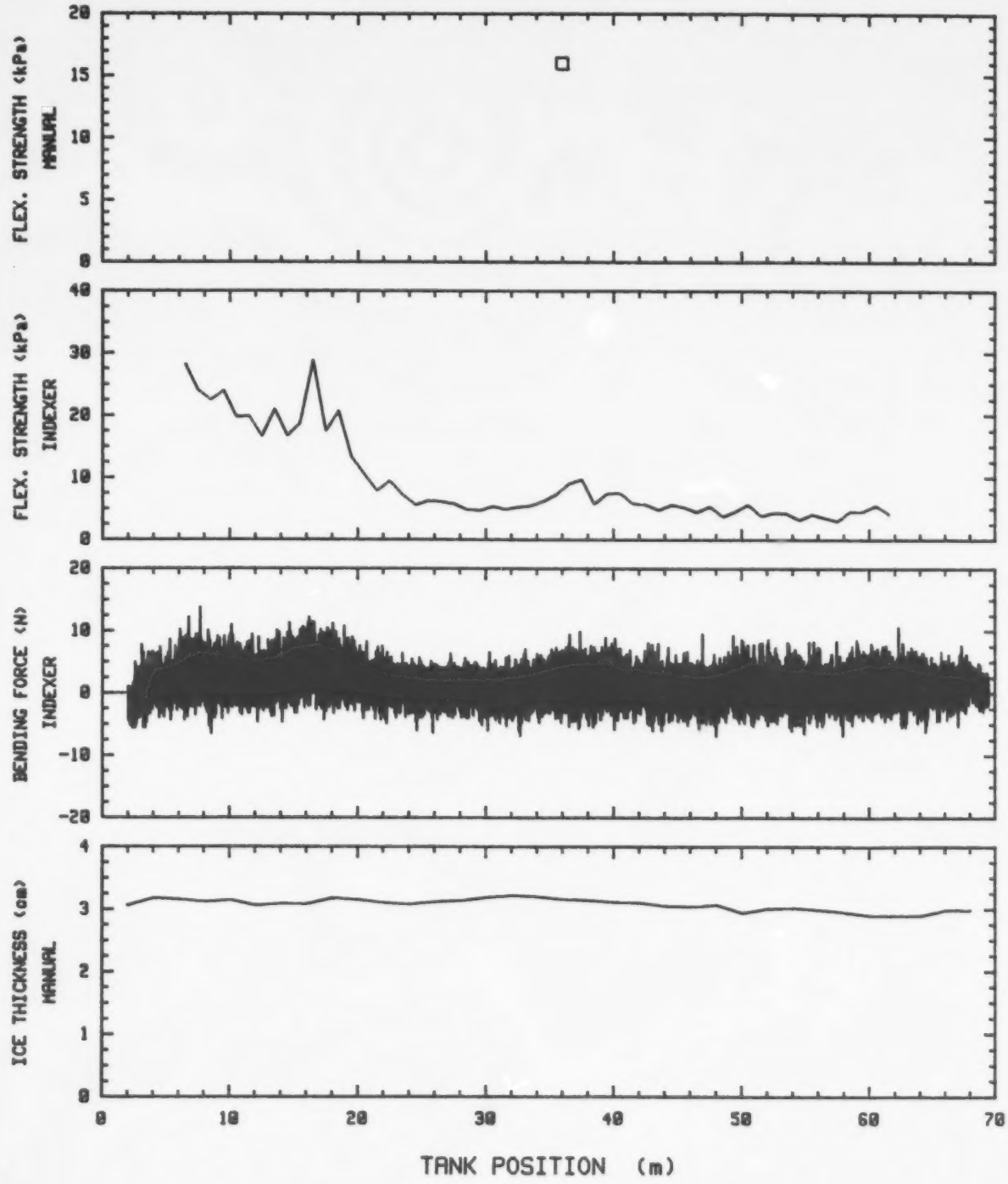


MELVILLE SHIPPING LTD

FIGURE A 2.15

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 24-SEP-1987 15:16:46

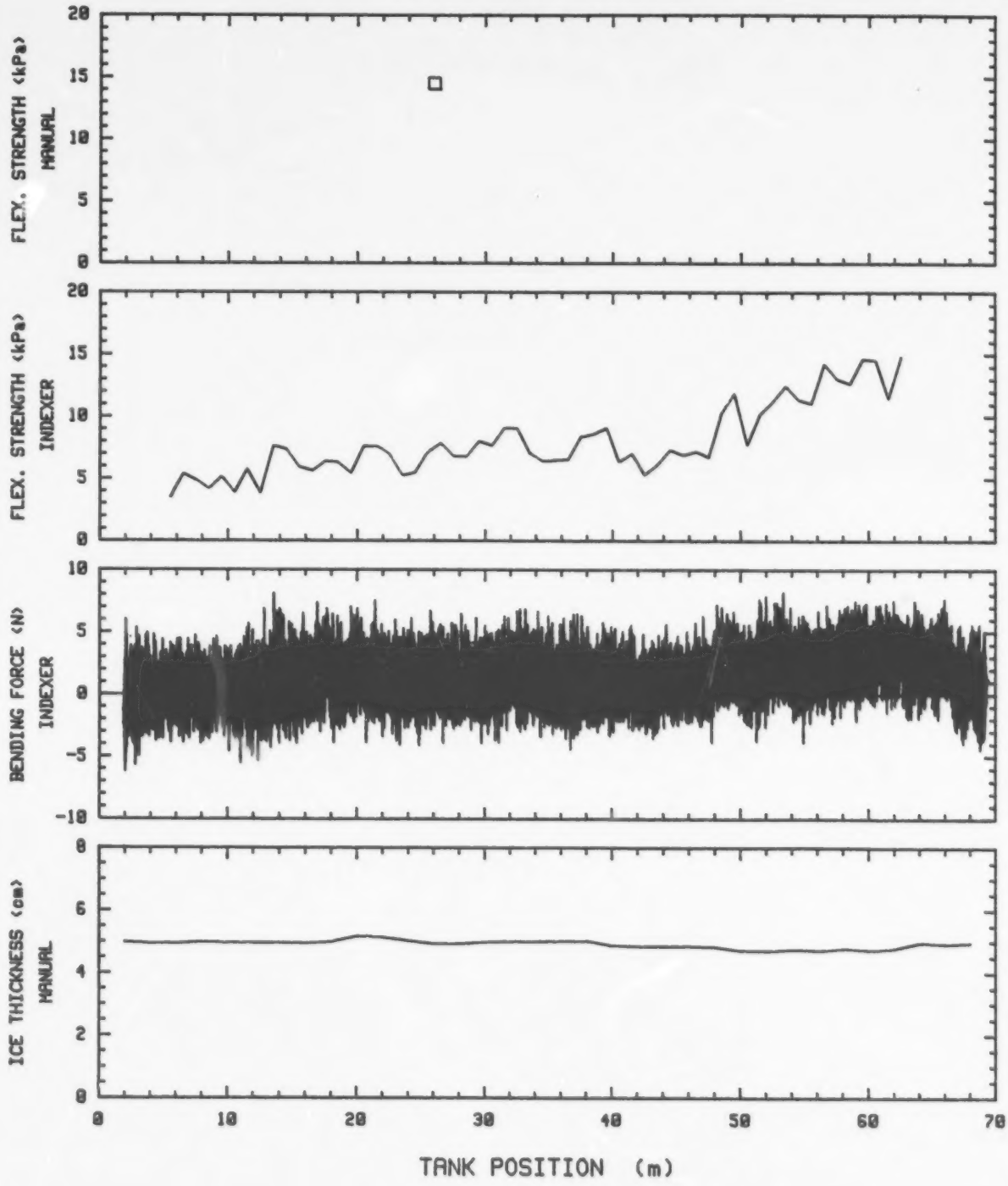


MELVILLE SHIPPING LTD

FIGURE A 2.16

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 6-OCT-1987 18:03:03

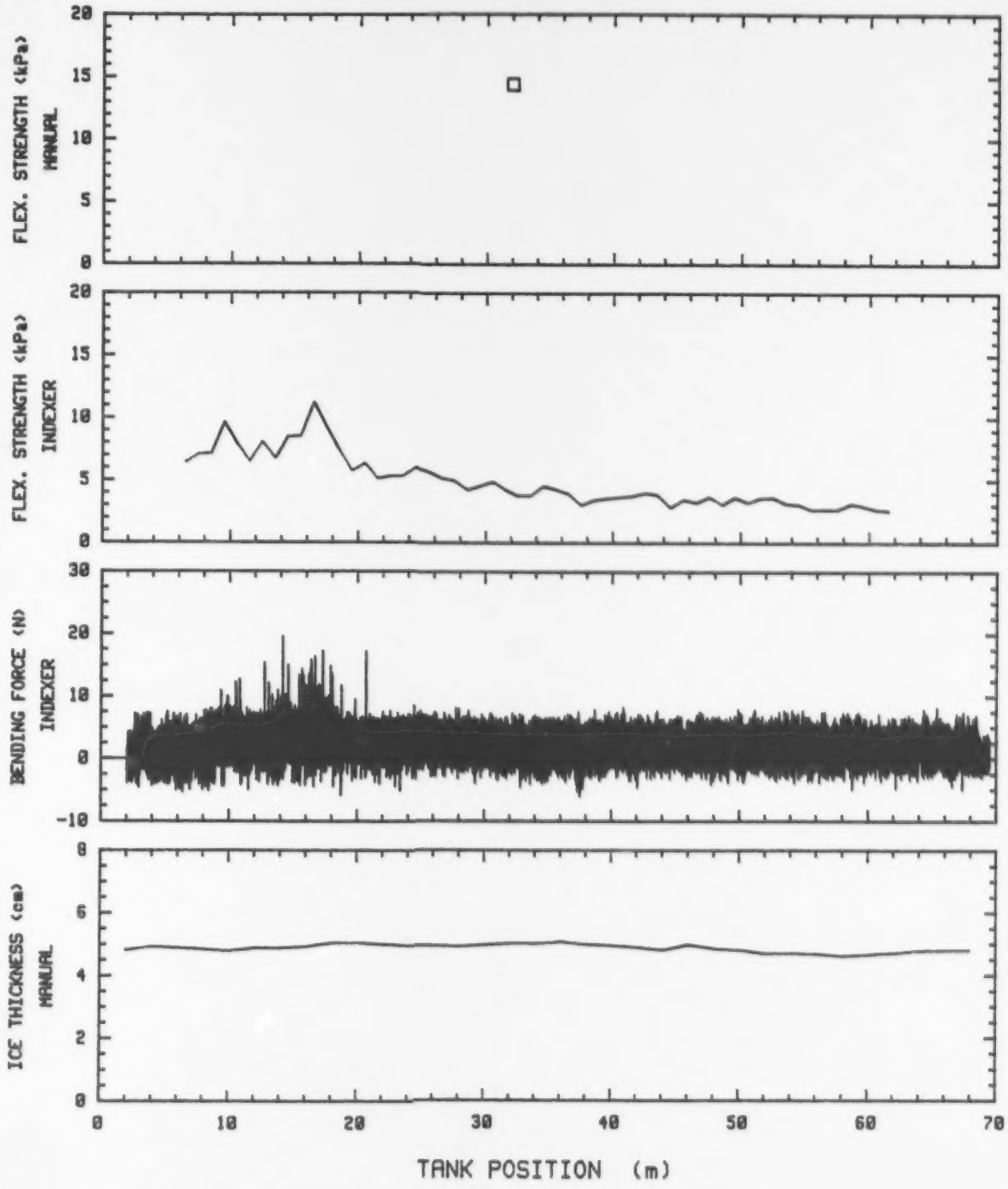


MELVILLE SHIPPING LTD

FIGURE A 2.17

ICE SHEET DATA - FLEXURAL STRENGTH

RUN 8-OCT-1987 16:59:26

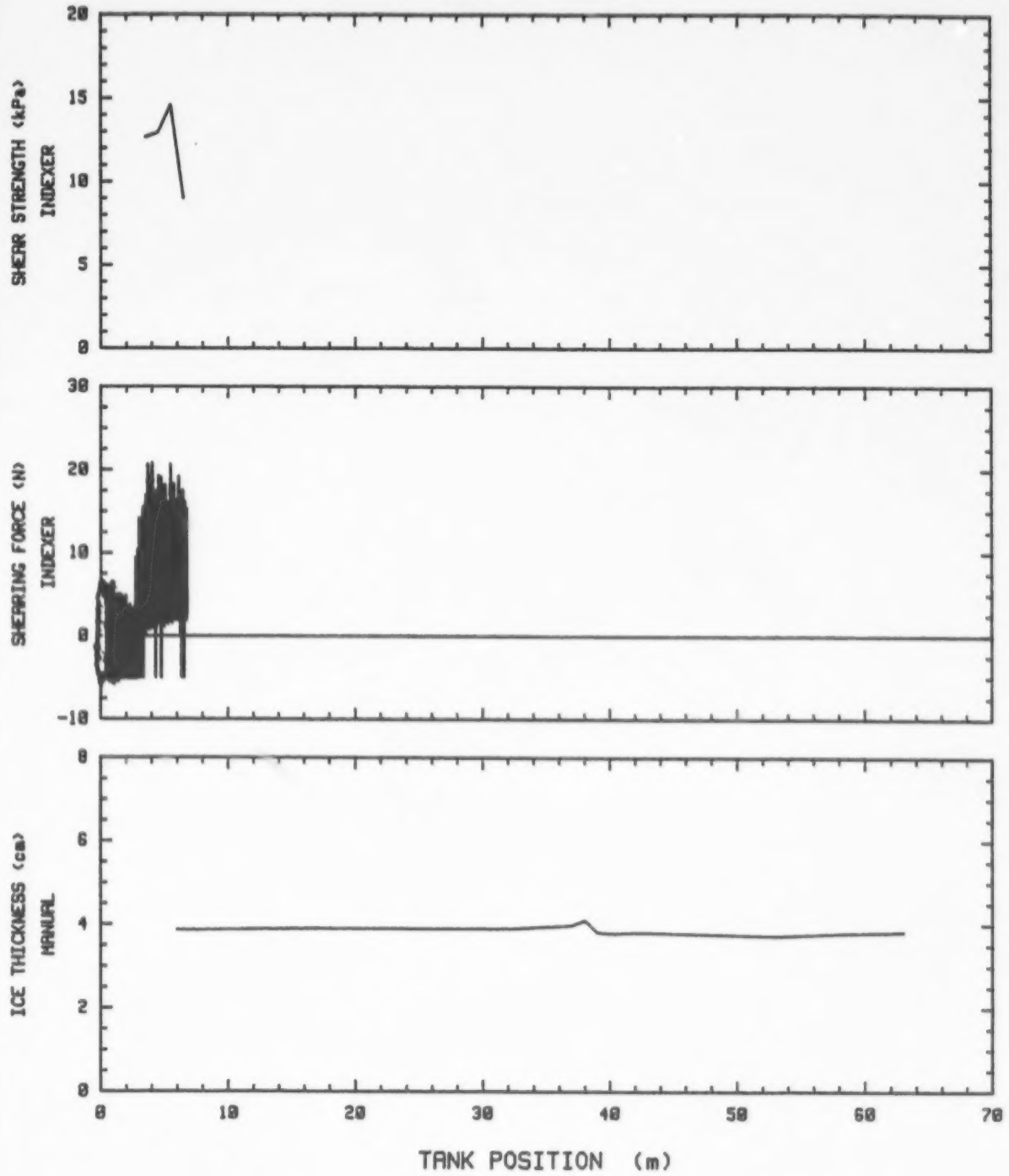


MELVILLE SHIPPING LTD

FIGURE A 2.18

ICE SHEET DATA - SHEAR STRENGTH

RUN 4-AUG-1987 09:51:46

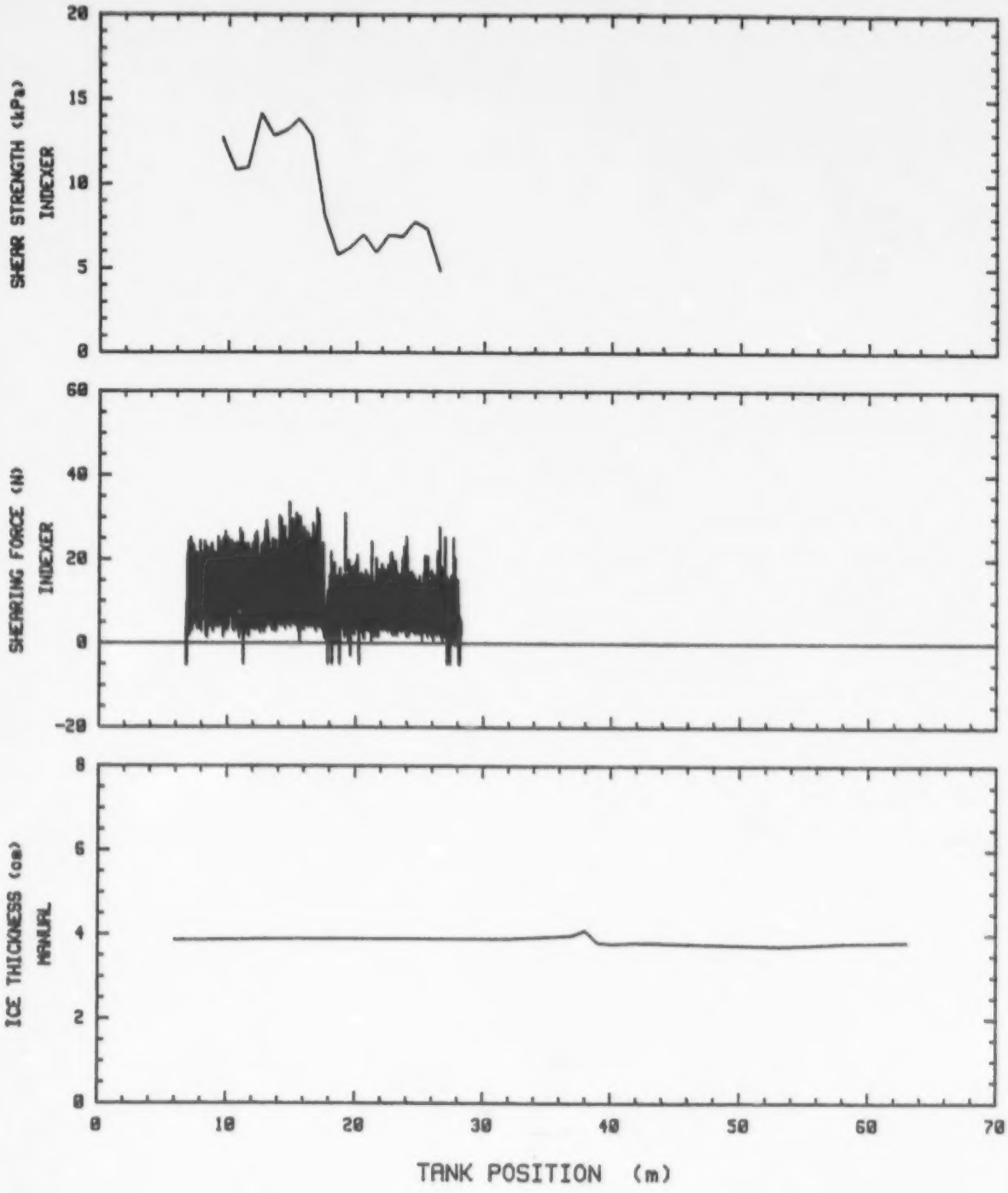


MELVILLE SHIPPING LTD

FIGURE A2.9

ICE SHEET DATA - SHEAR STRENGTH

RUN 4-AUG-1987 09:55:39

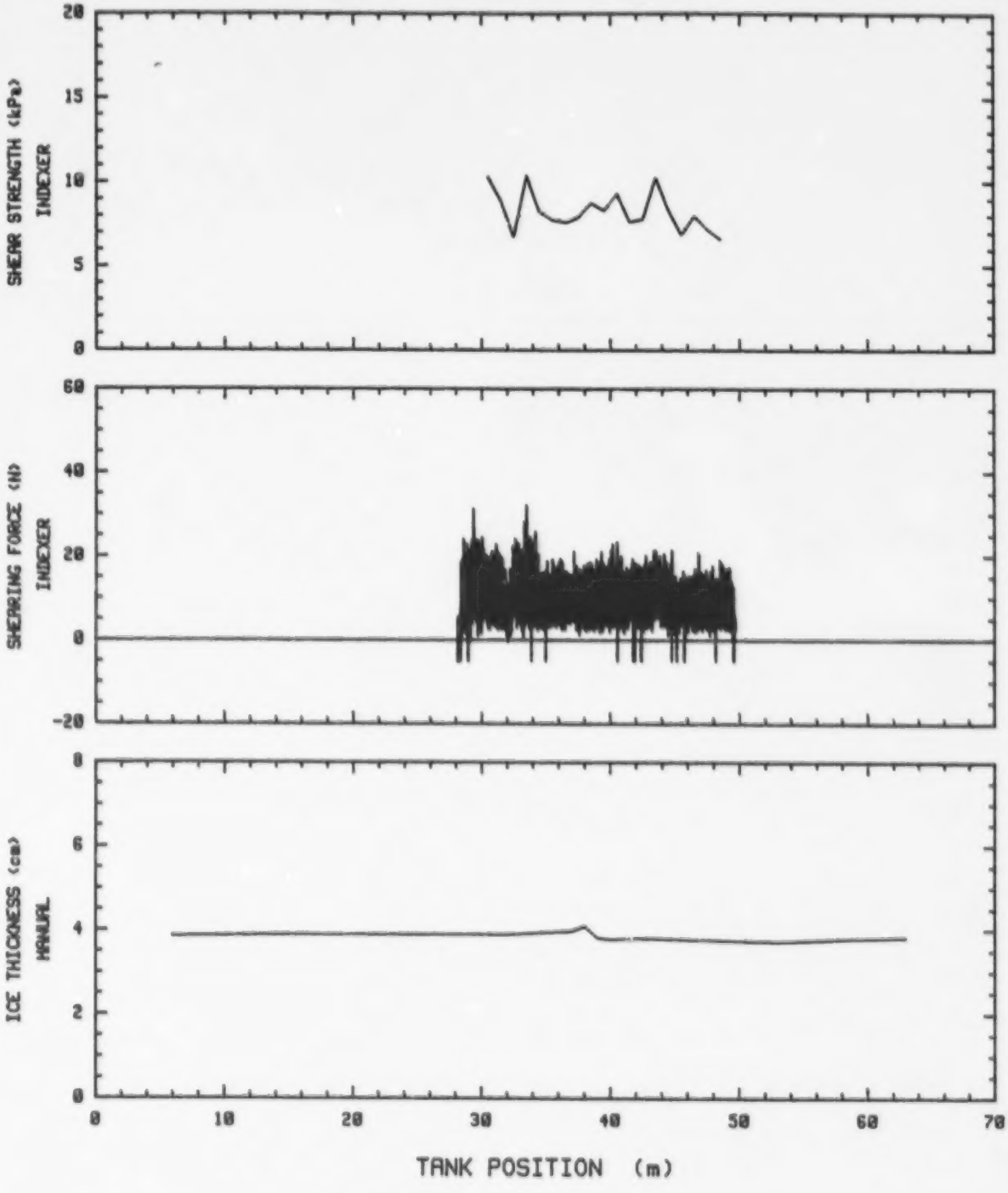


MELVILLE SHIPPING LTD

FIGURE A 2.20

ICE SHEET DATA - SHEAR STRENGTH

RUN 4-AUG-1987 11:54:53

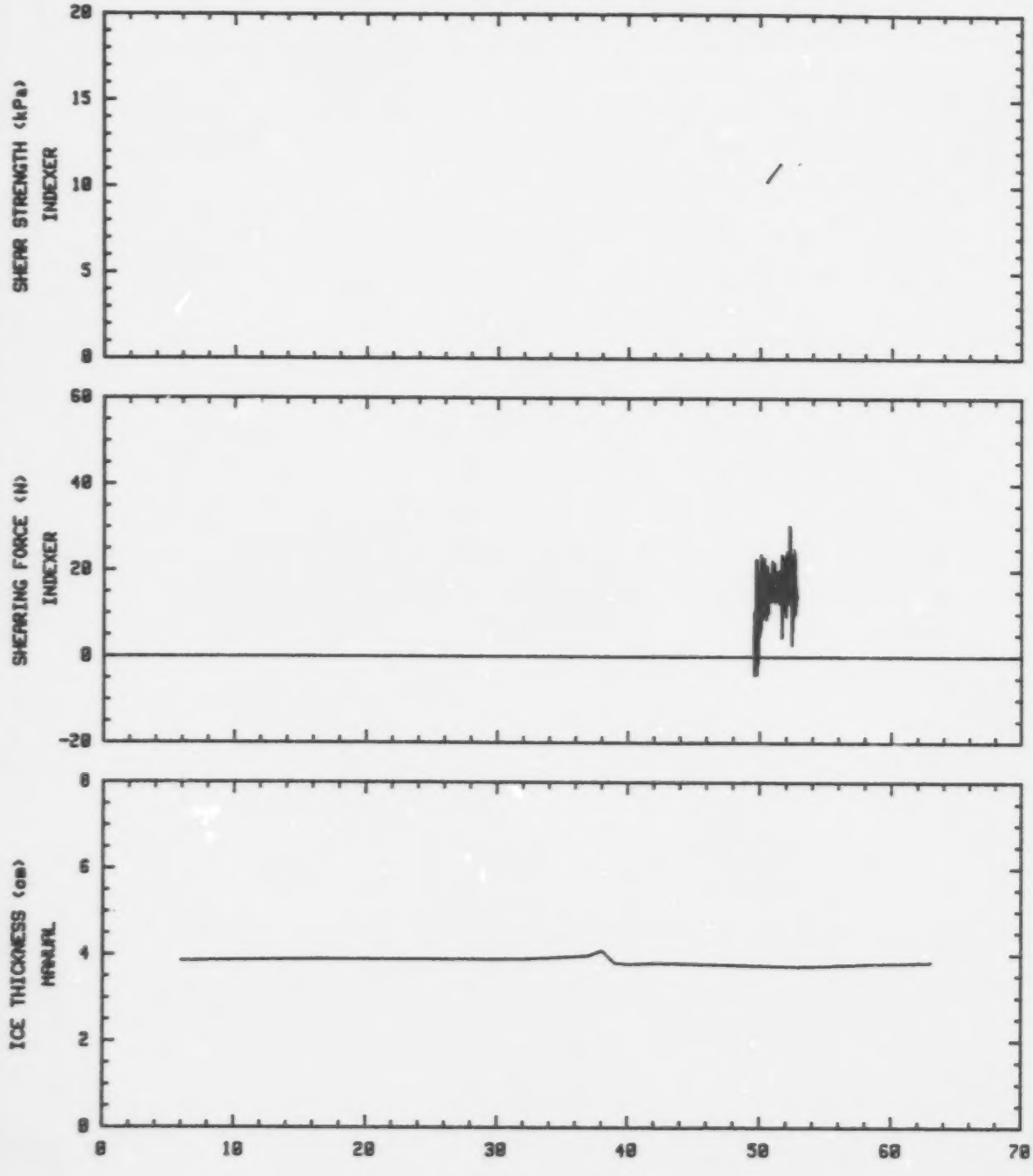


MELVILLE SHIPPING LTD

FIGURE A 2.2

ICE SHEET DATA - SHEAR STRENGTH

RUN 4-AUG-1987 14:32:14

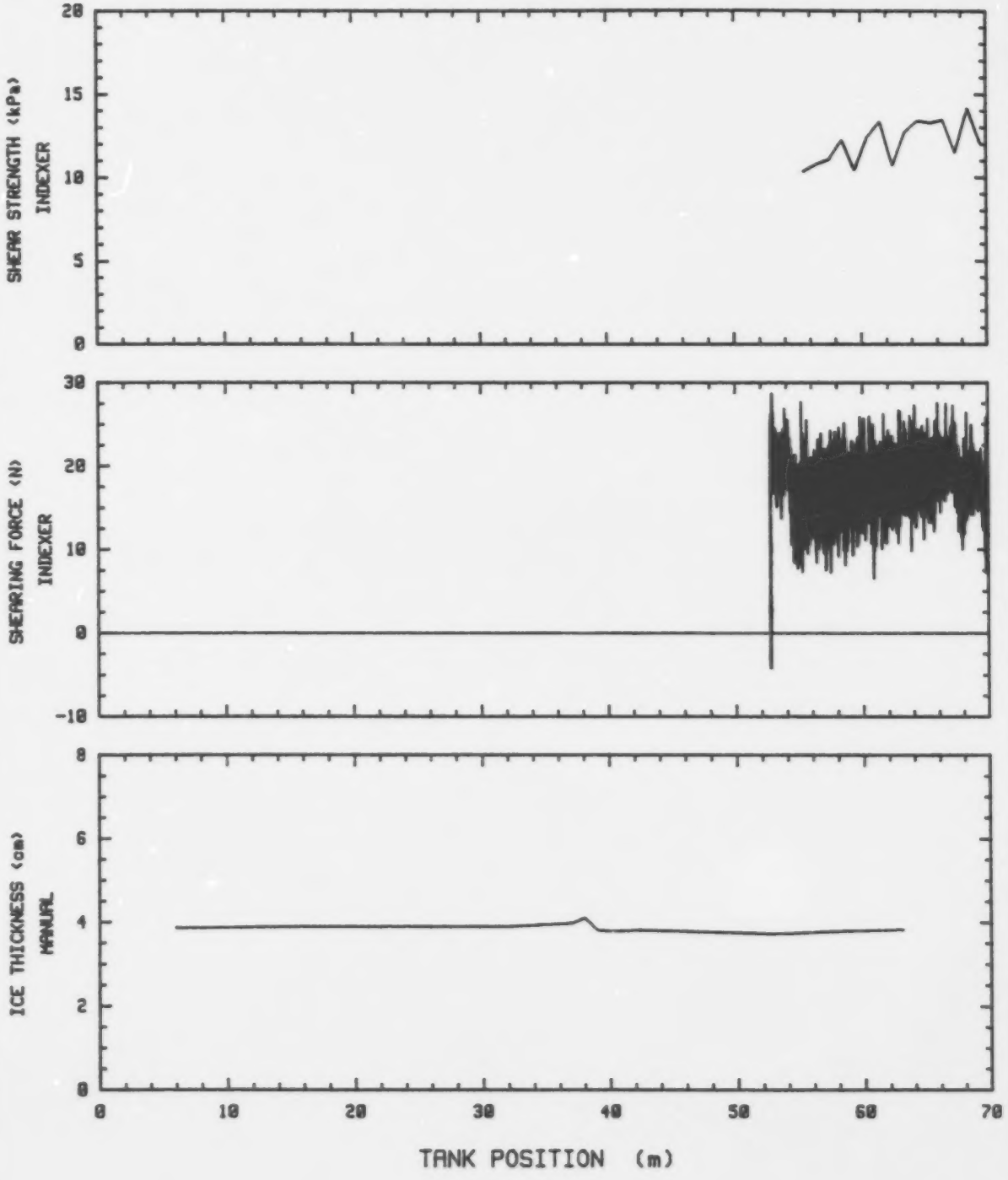


MELVILLE SHIPPING LTD

FIGURE A.2.02

ICE SHEET DATA - SHEAR STRENGTH

RUN 4-AUG-1987 14:36:04

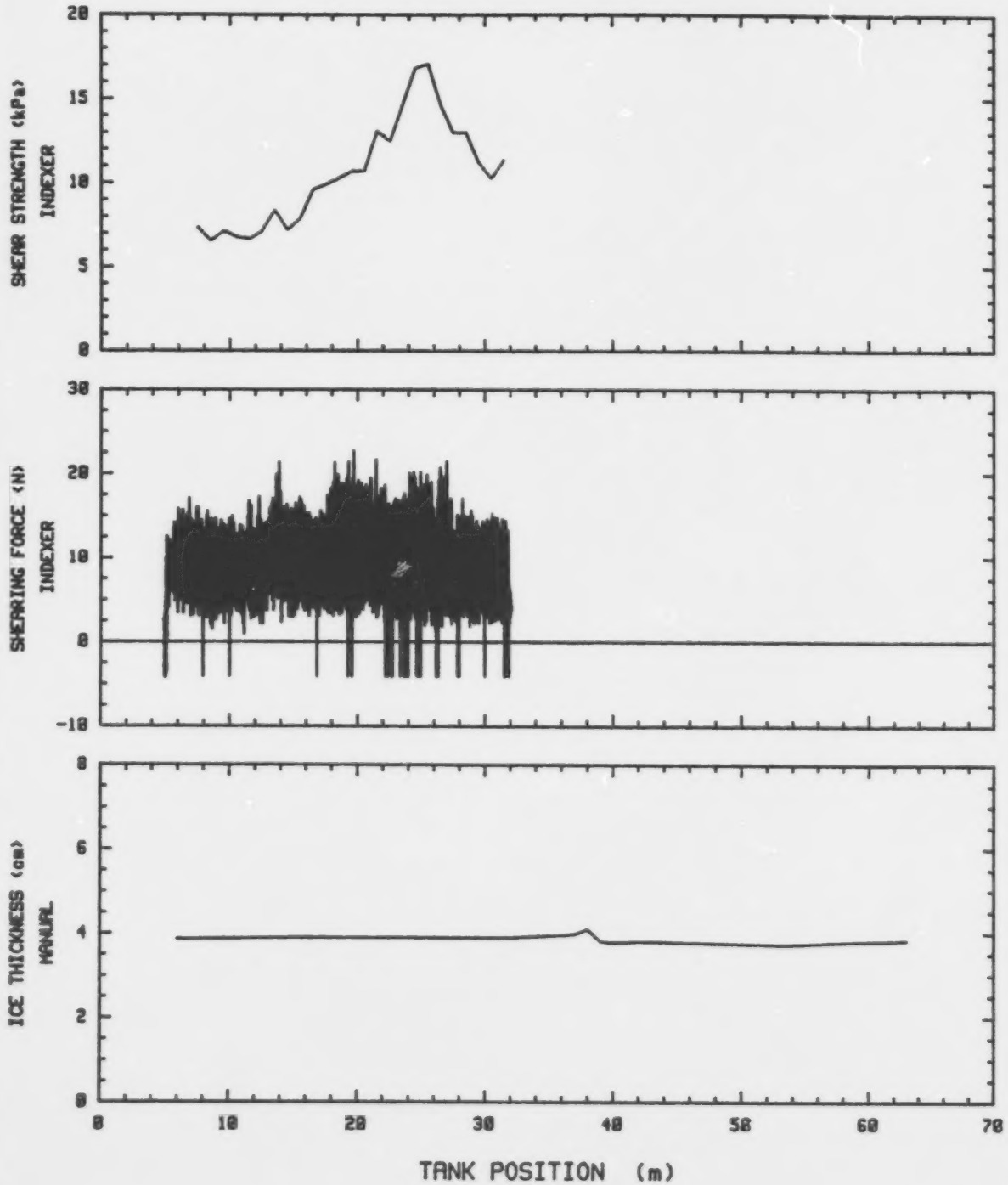


MELVILLE SHIPPING LTD

FIGURE A2.23

ICE SHEET DATA - SHEAR STRENGTH

RUN 4-AUG-1987 16:00:53

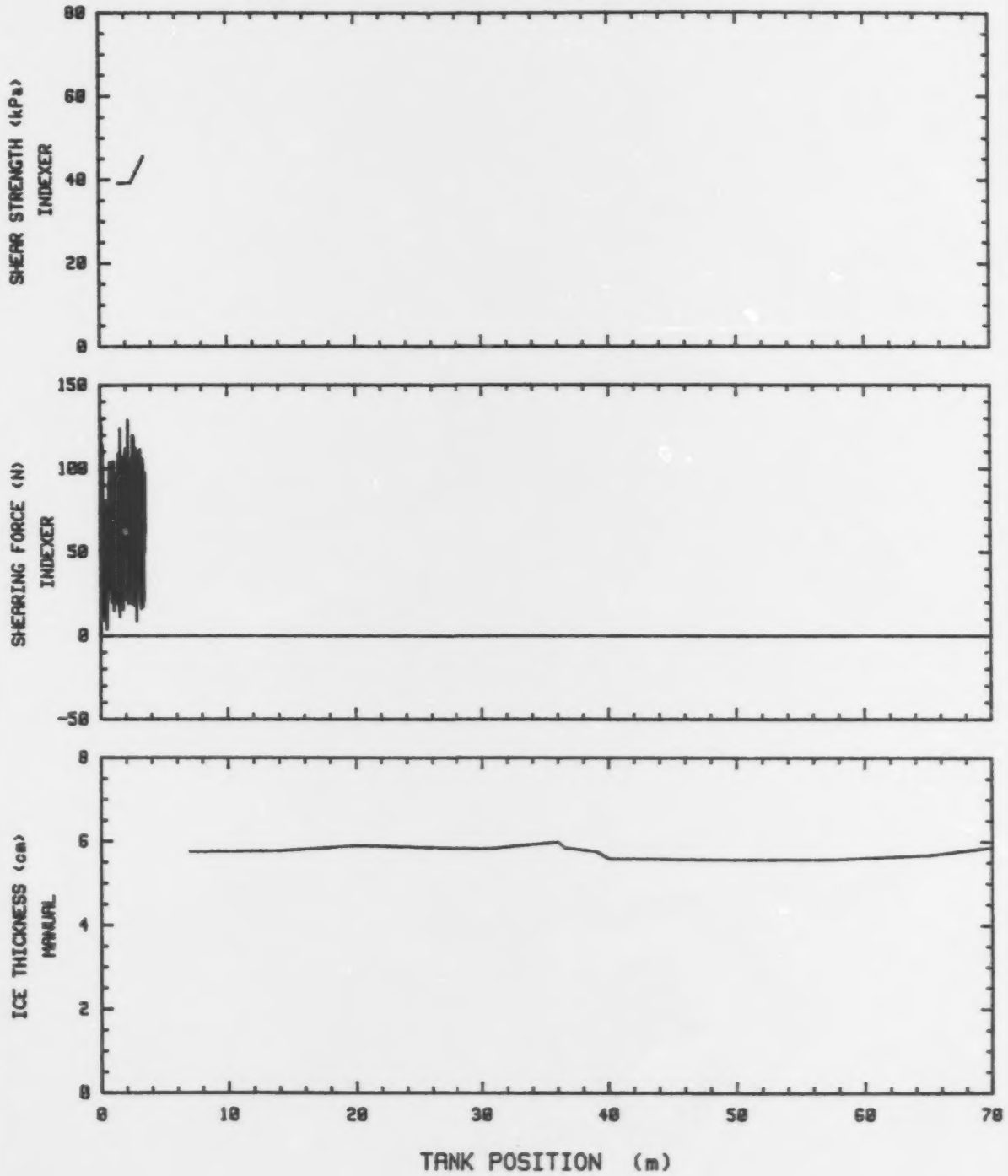


MELVILLE SHIPPING LTD

FIGURE A 2.24

ICE SHEET DATA - SHEAR STRENGTH

RUN 7-AUG-1987 13:35:29

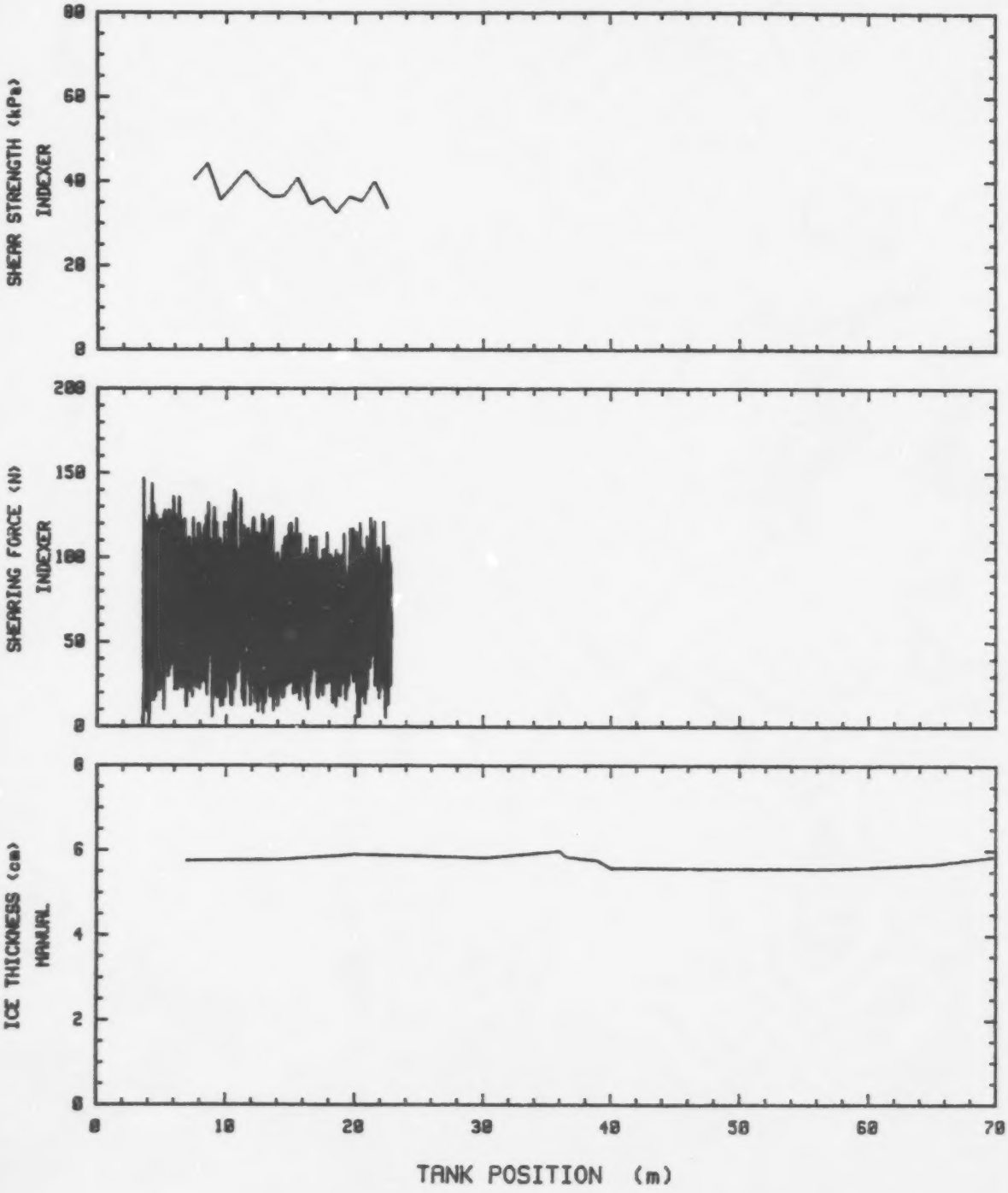


MELVILLE SHIPPING LTD

FIGURE A.2.25

ICE SHEET DATA - SHEAR STRENGTH

RUN 7-AUG-1987 13:45:49

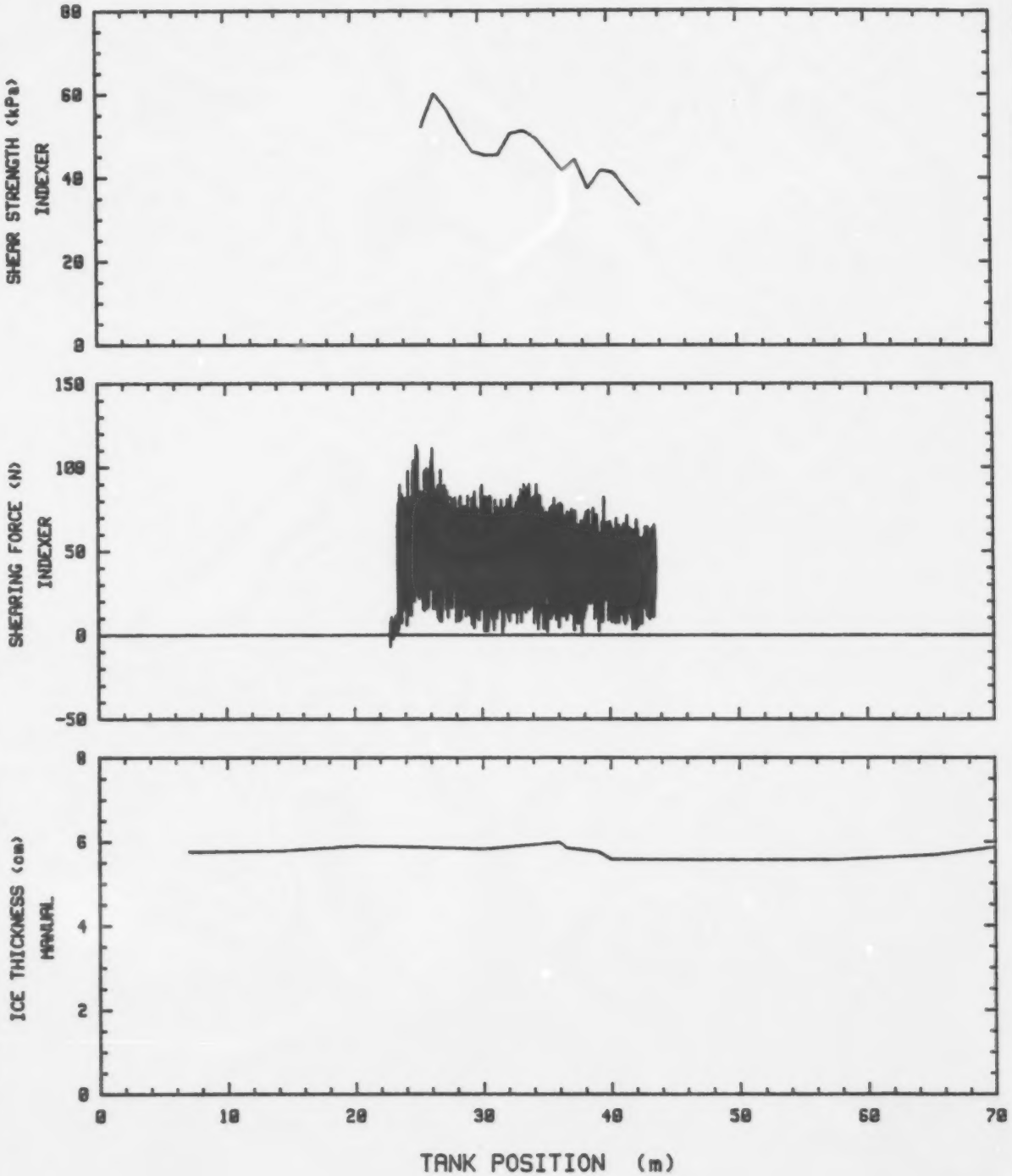


MELVILLE SHIPPING LTD

FIGURE A 2.26

ICE SHEET DATA - SHEAR STRENGTH

RUN 7-AUG-1987 15:42:47

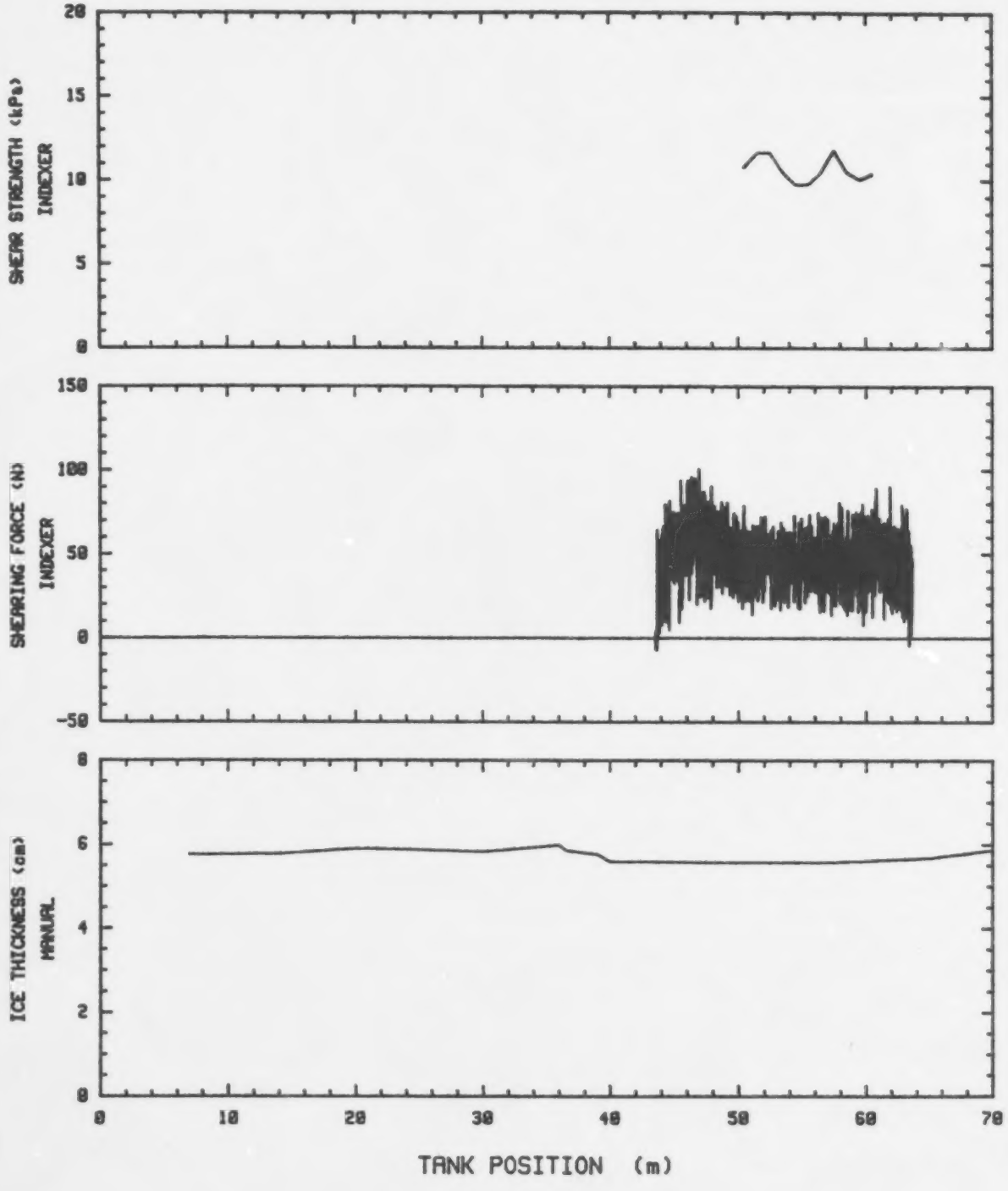


MELVILLE SHIPPING LTD

FIGURE A2.27

ICE SHEET DATA - SHEAR STRENGTH

RUN 7-AUG-1987 16:34:48

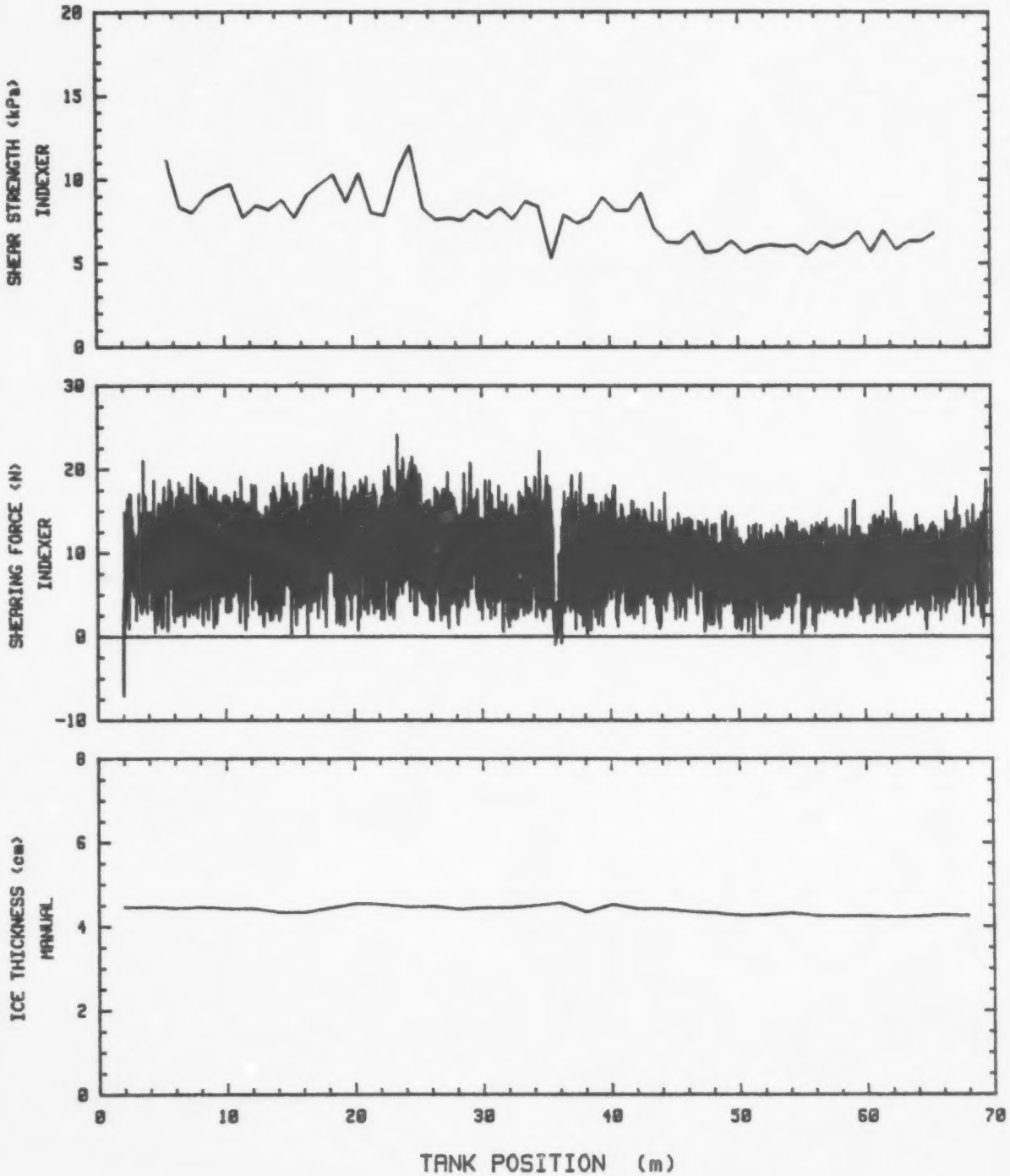


MELVILLE SHIPPING LTD

FIGURE A 2.28

ICE SHEET DATA - SHEAR STRENGTH

RUN 15-SEP-1987 12:33:15

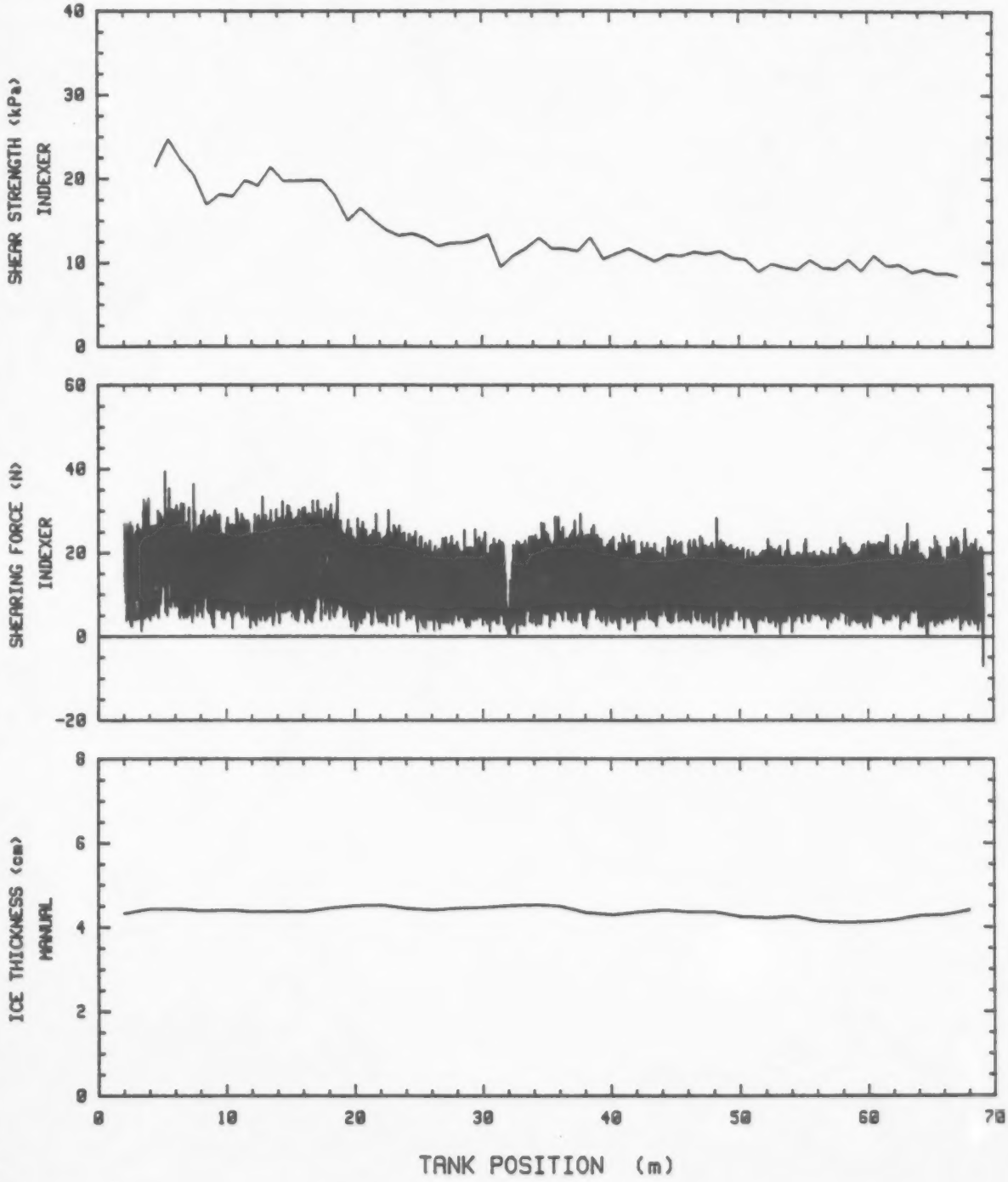


MELVILLE SHIPPING LTD

FIGURE A2.23

ICE SHEET DATA - SHEAR STRENGTH

RUN 16-SEP-1987 17:04:34

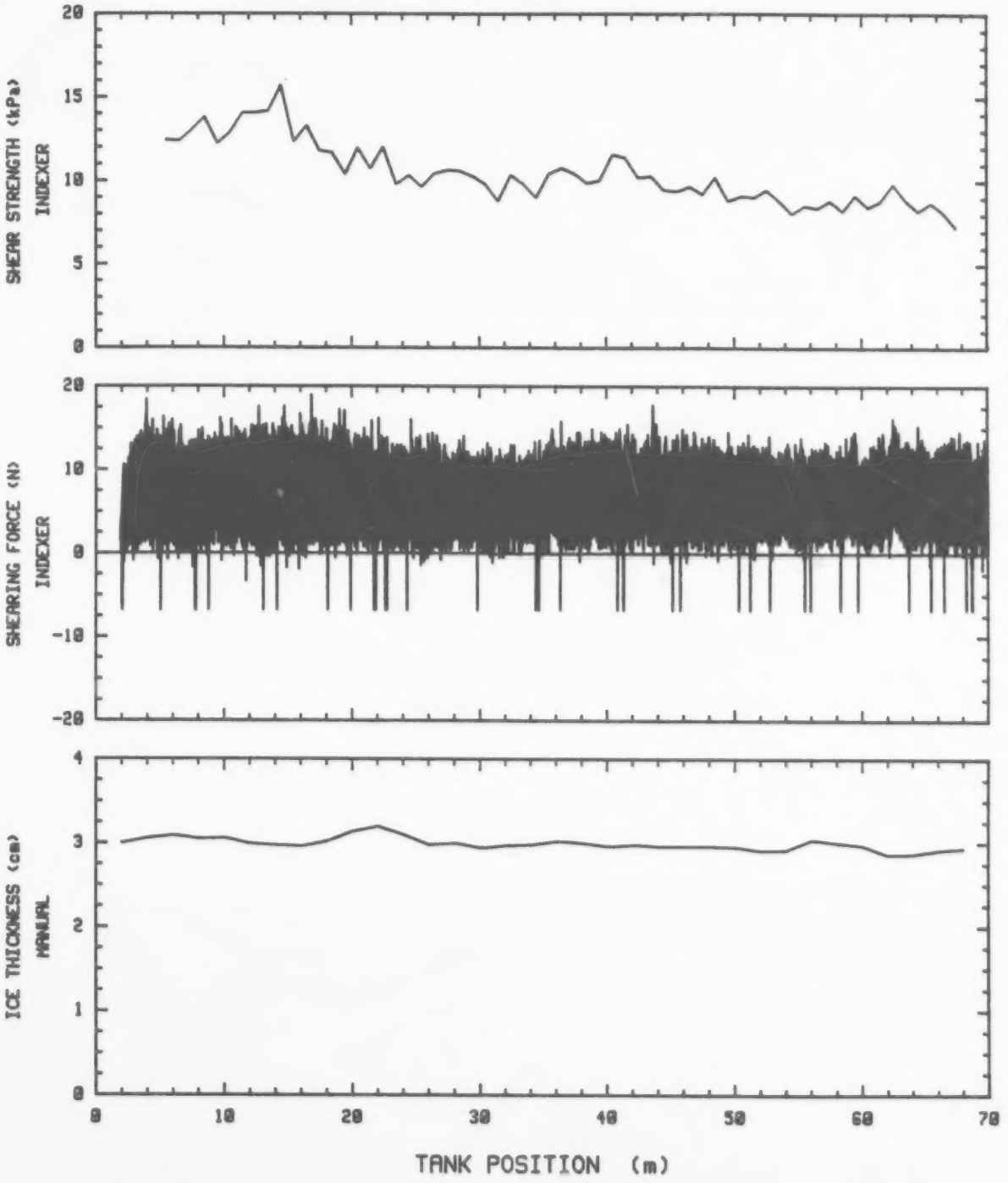


MELVILLE SHIPPING LTD

FIGURE A 2.30

ICE SHEET DATA - SHEAR STRENGTH

RUN 17-SEP-1987 13:18:06

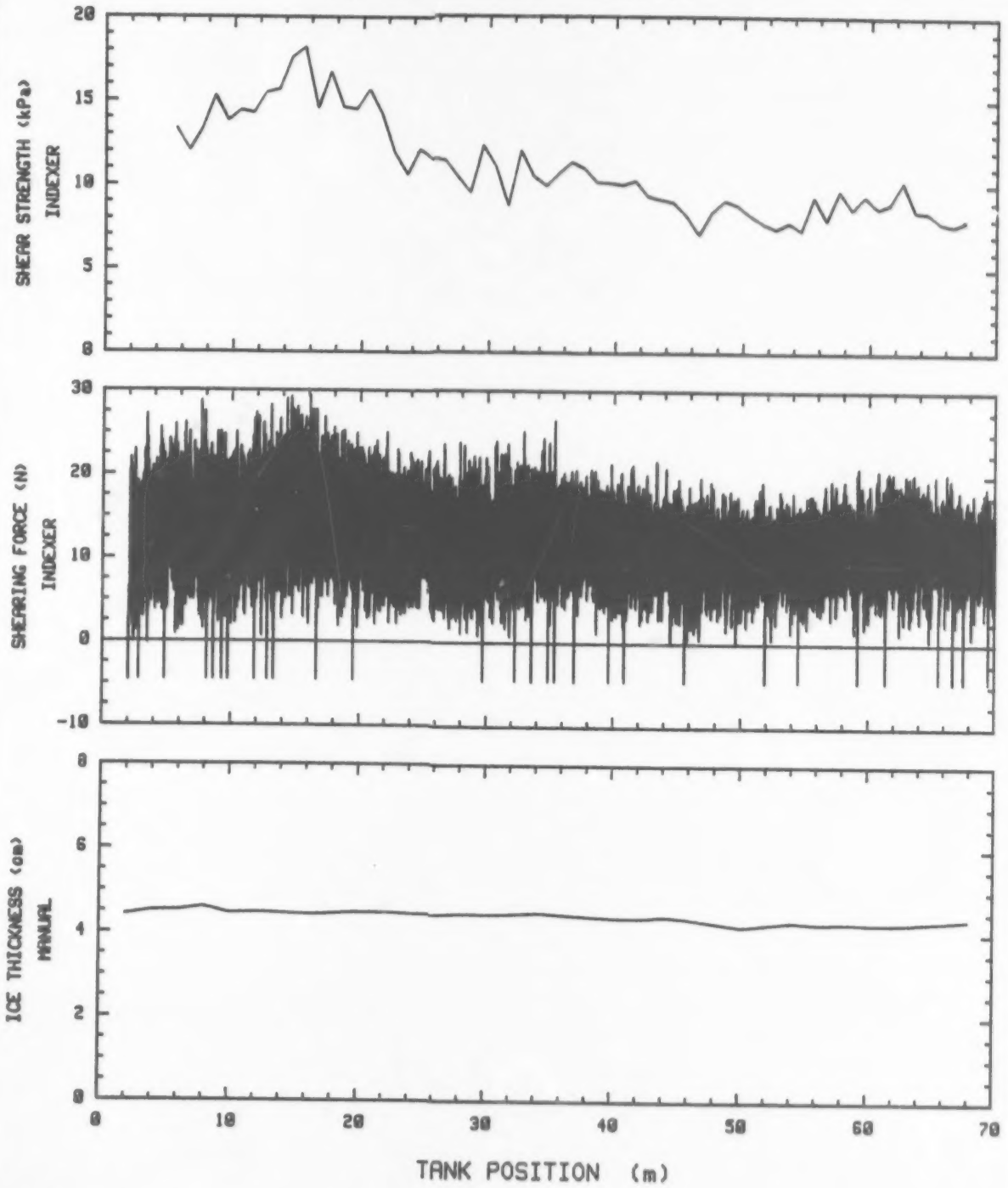


MELVILLE SHIPPING LTD

FIGURE A2.3

ICE SHEET DATA - SHEAR STRENGTH

RUN 22-SEP-1987 12:00:19

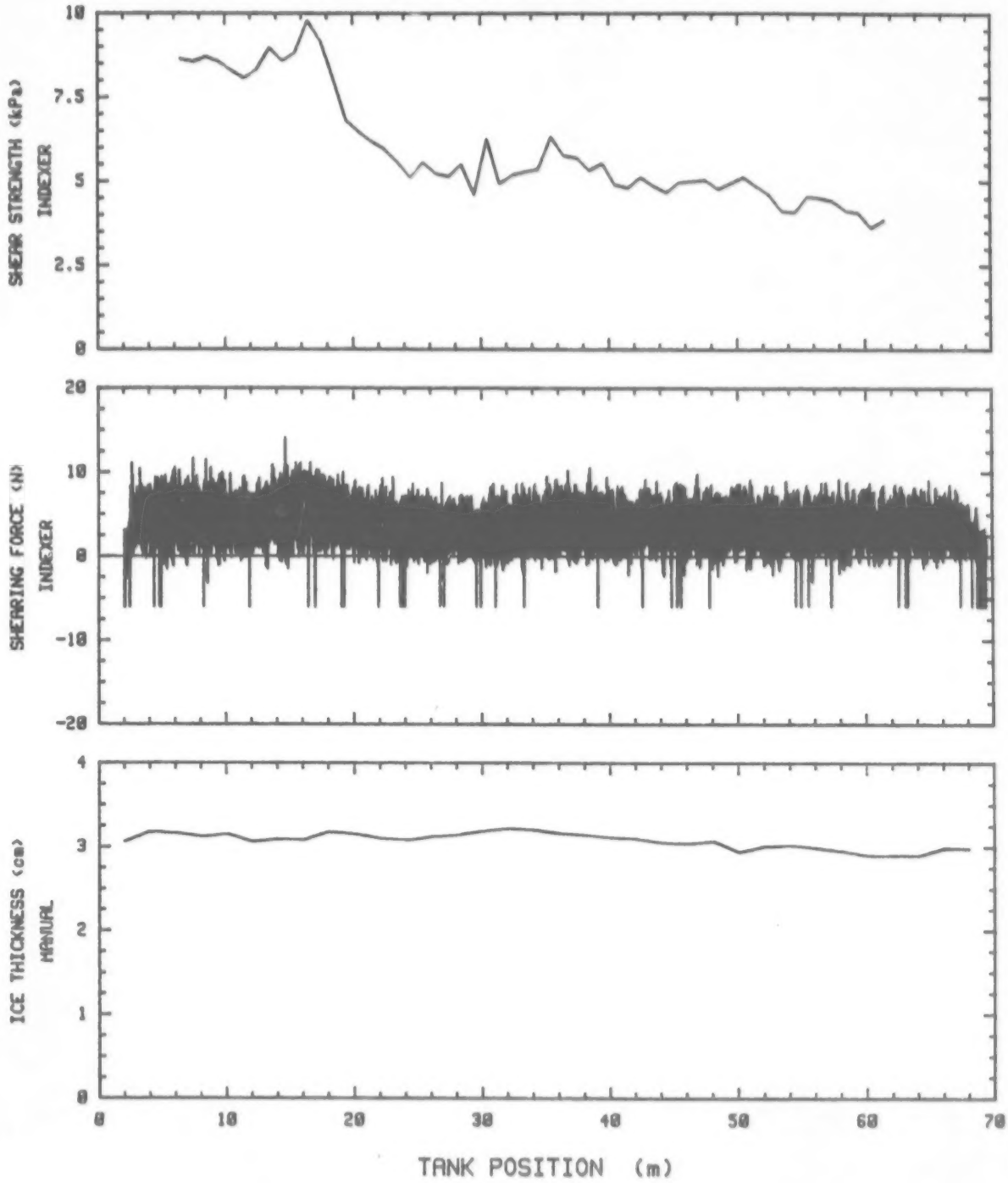


MELVILLE SHIPPING LTD

FIGURE A2.32

ICE SHEET DATA - SHEAR STRENGTH

RUN 24-SEP-1987 15:16:46

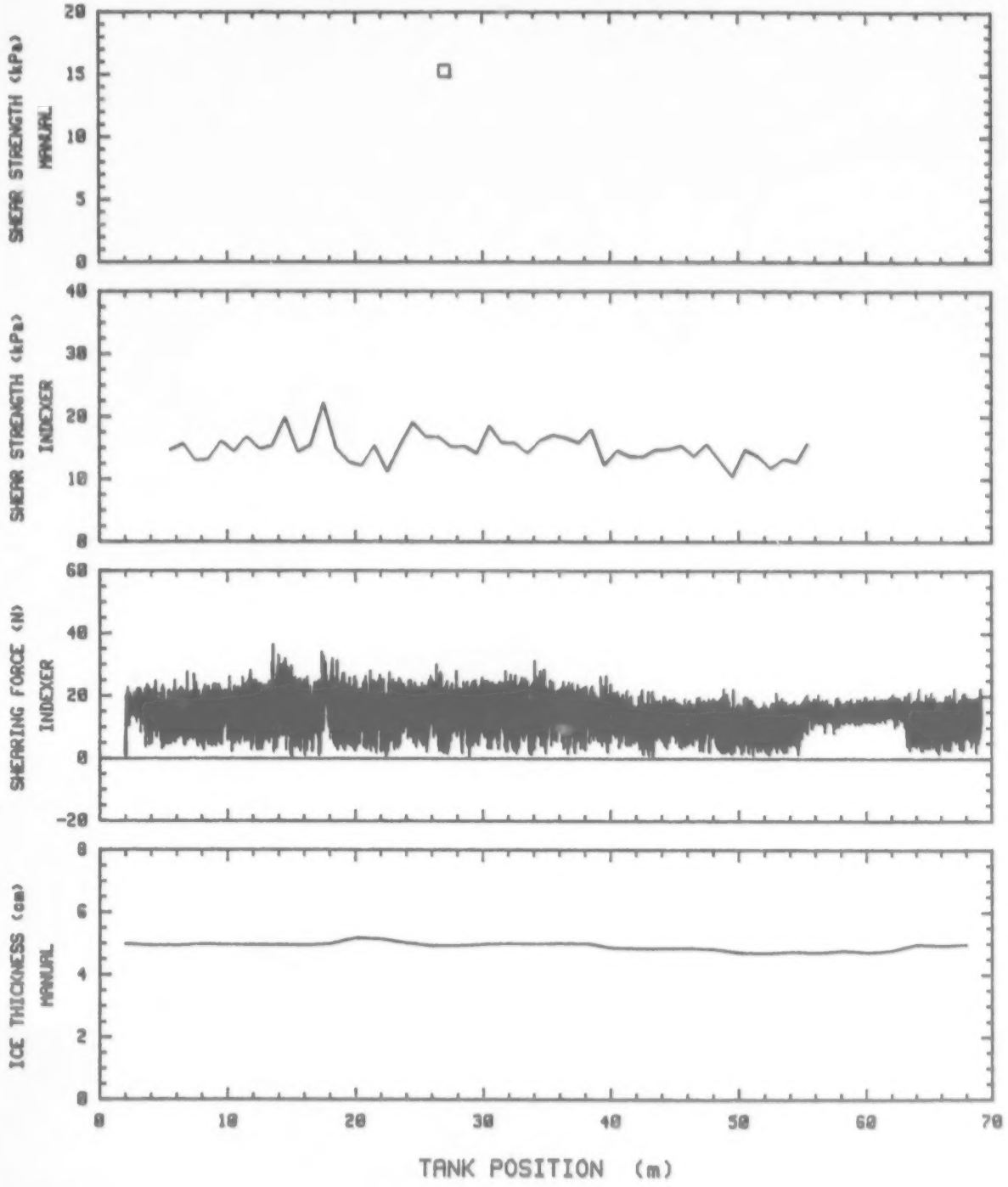


MELVILLE SHIPPING LTD

FIGURE A 2.33

ICE SHEET DATA - SHEAR STRENGTH

RUN 6-OCT-1987 18:03:03

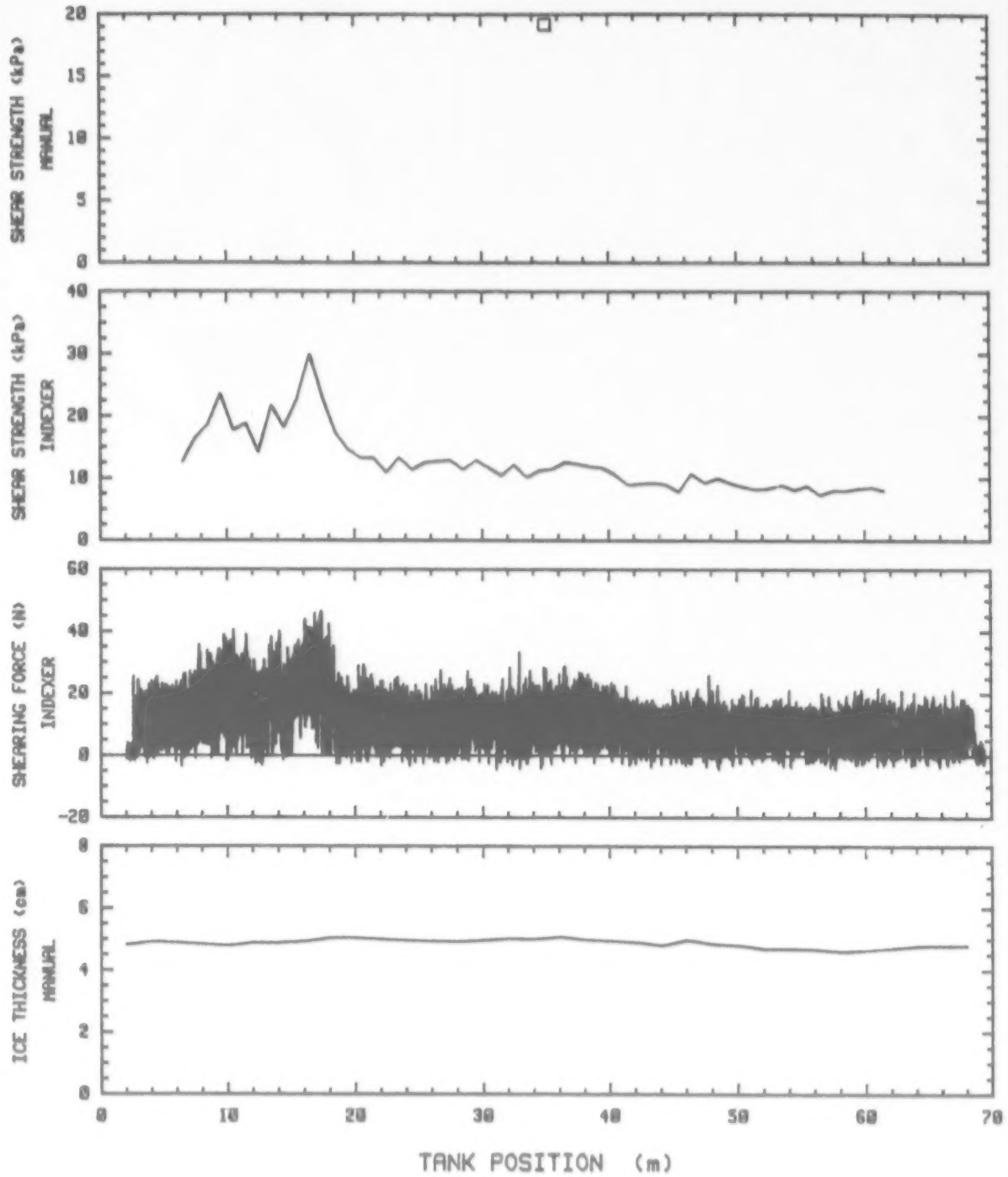


MELVILLE SHIPPING LTD

FIGURE A 2.34

ICE SHEET DATA - SHEAR STRENGTH

RUN 8-OCT-1987 16:59:26

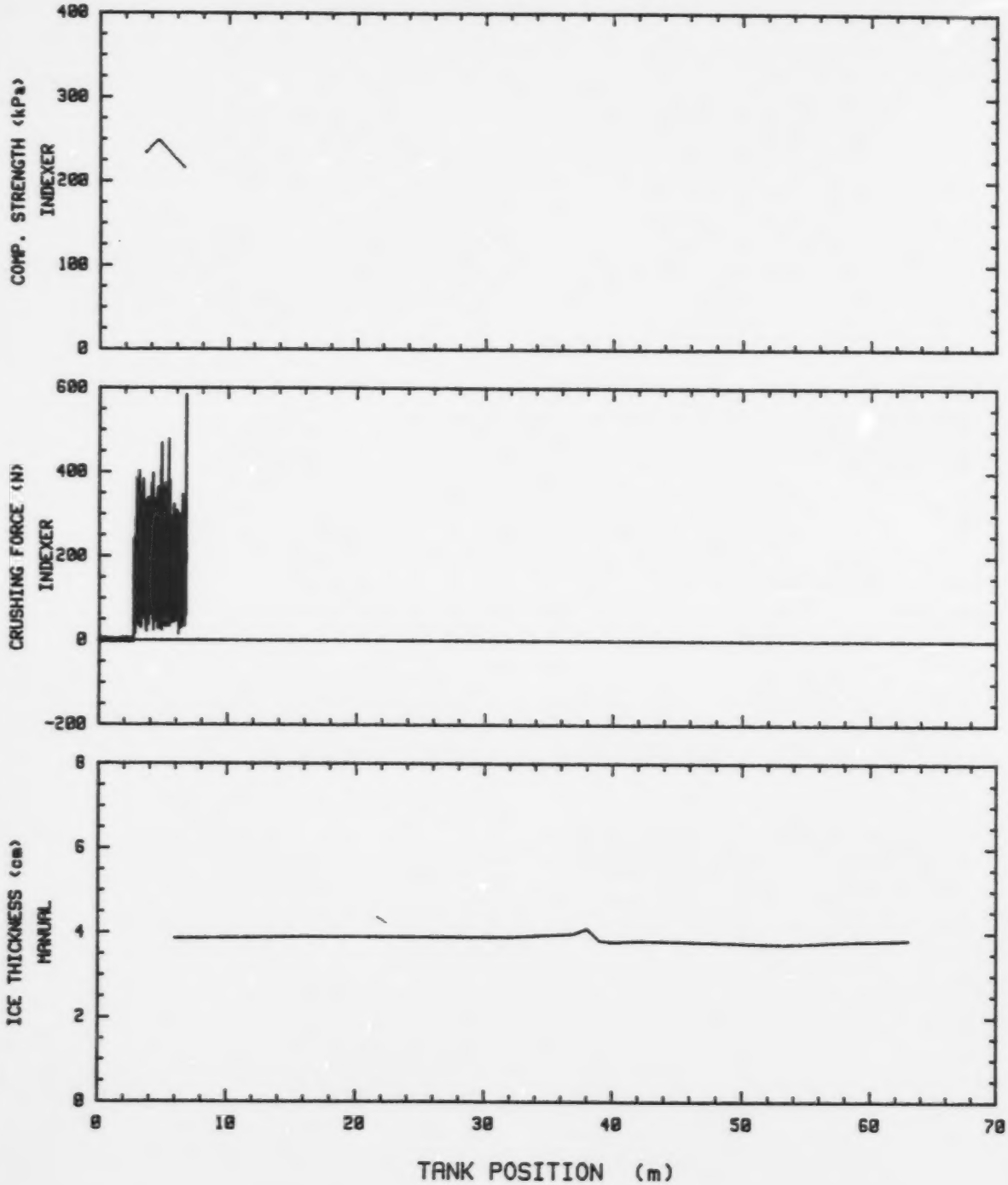


MELVILLE SHIPPING LTD

FIGURE A2.35

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 4-AUG-1987 09:51:46

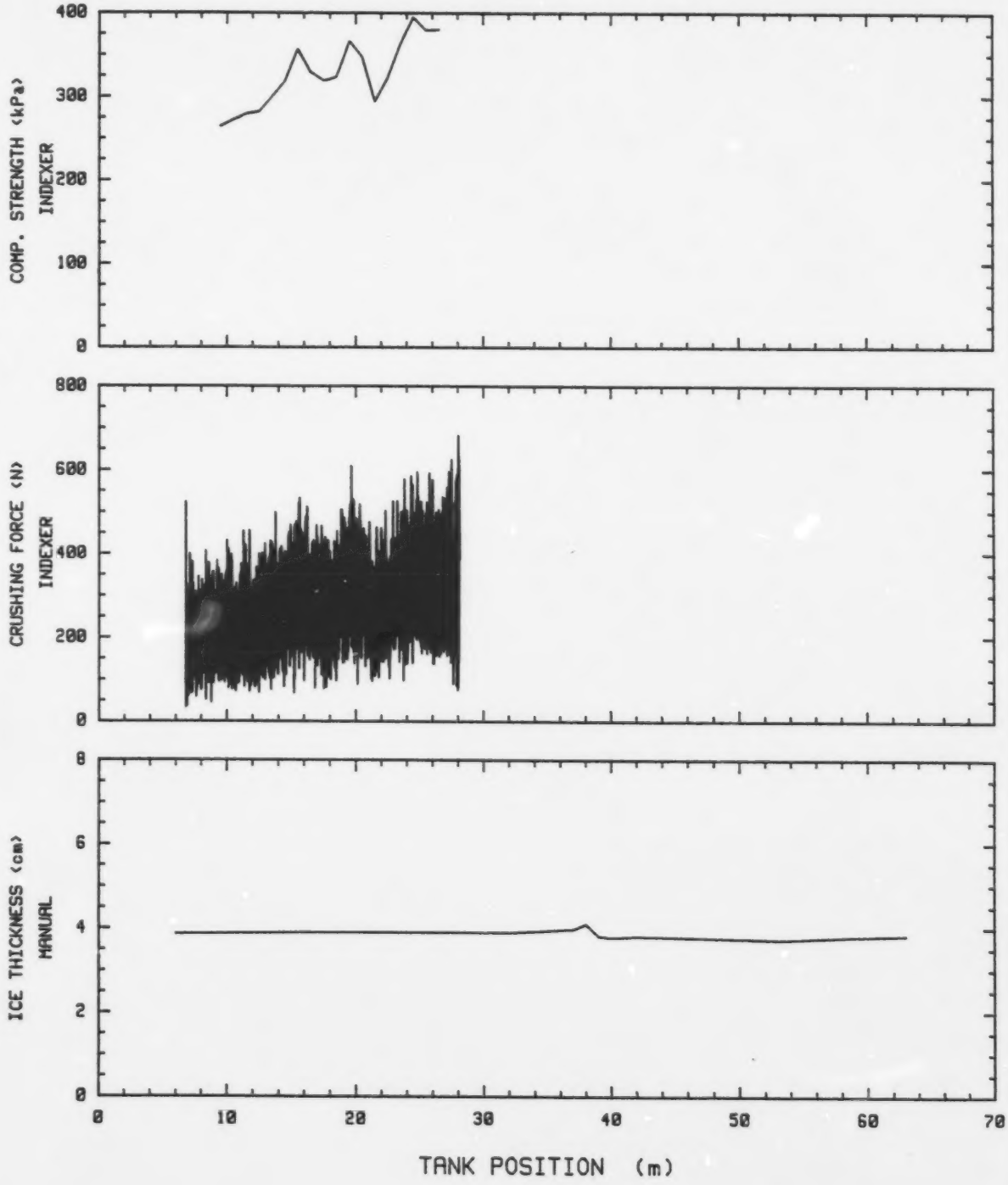


MELVILLE SHIPPING LTD

FIGURE A 2.36

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 4-AUG-1987 09:55:39

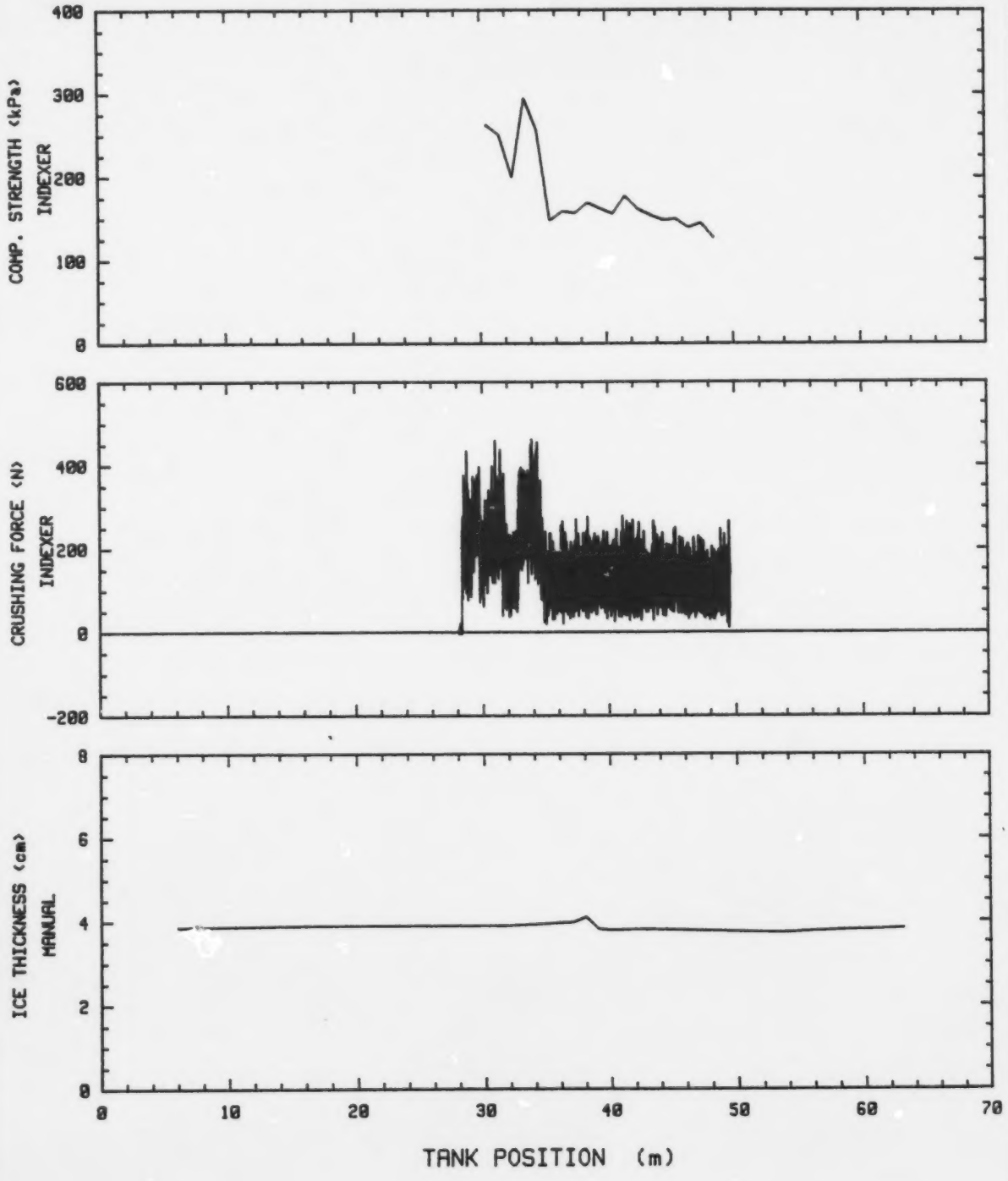


MELVILLE SHIPPING LTD

FIGURE A 2.37

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 4-AUG-1987 11:54:53

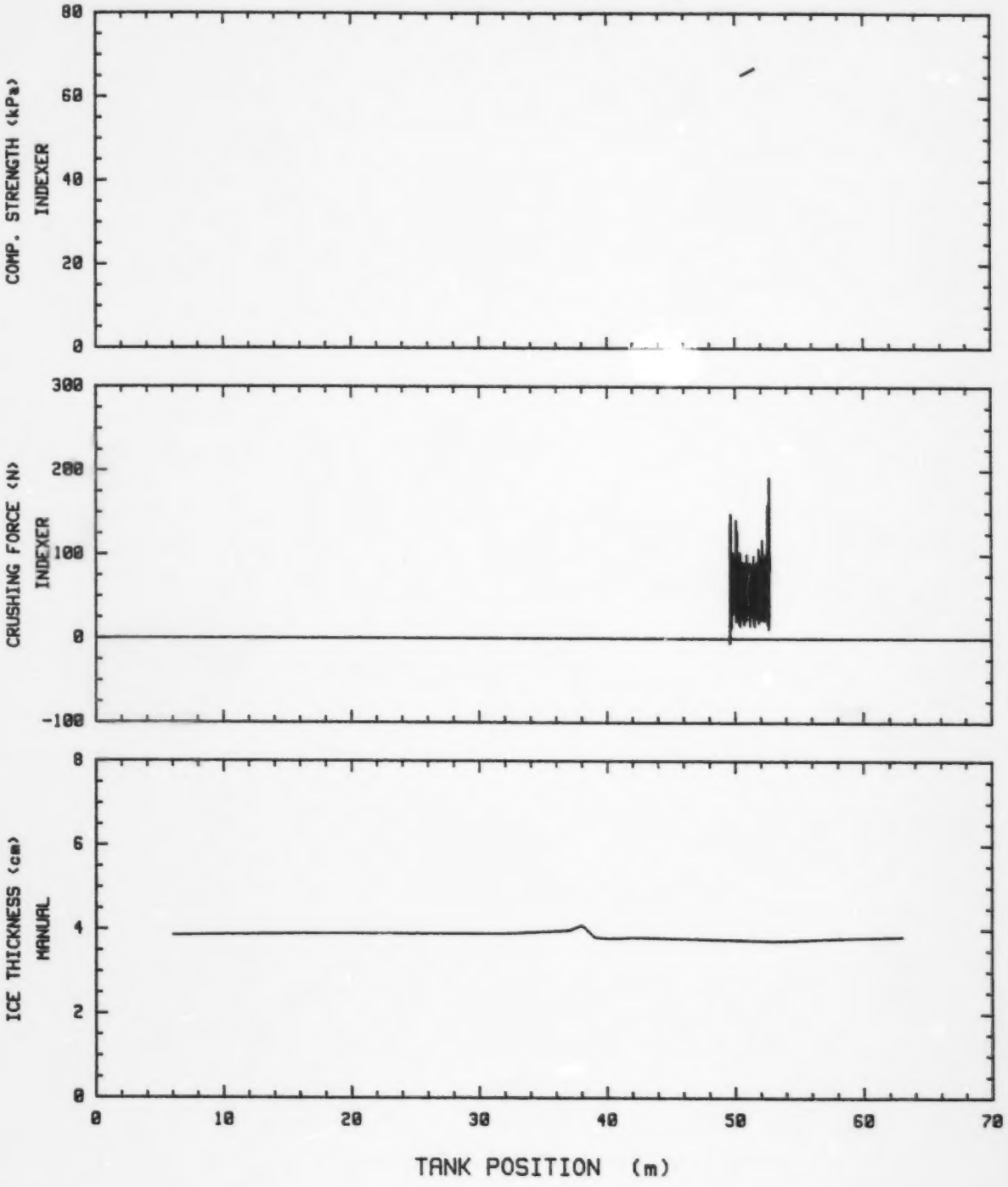


MELVILLE SHIPPING LTD

FIGURE A 2.38

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 4-AUG-1987 14:32:14

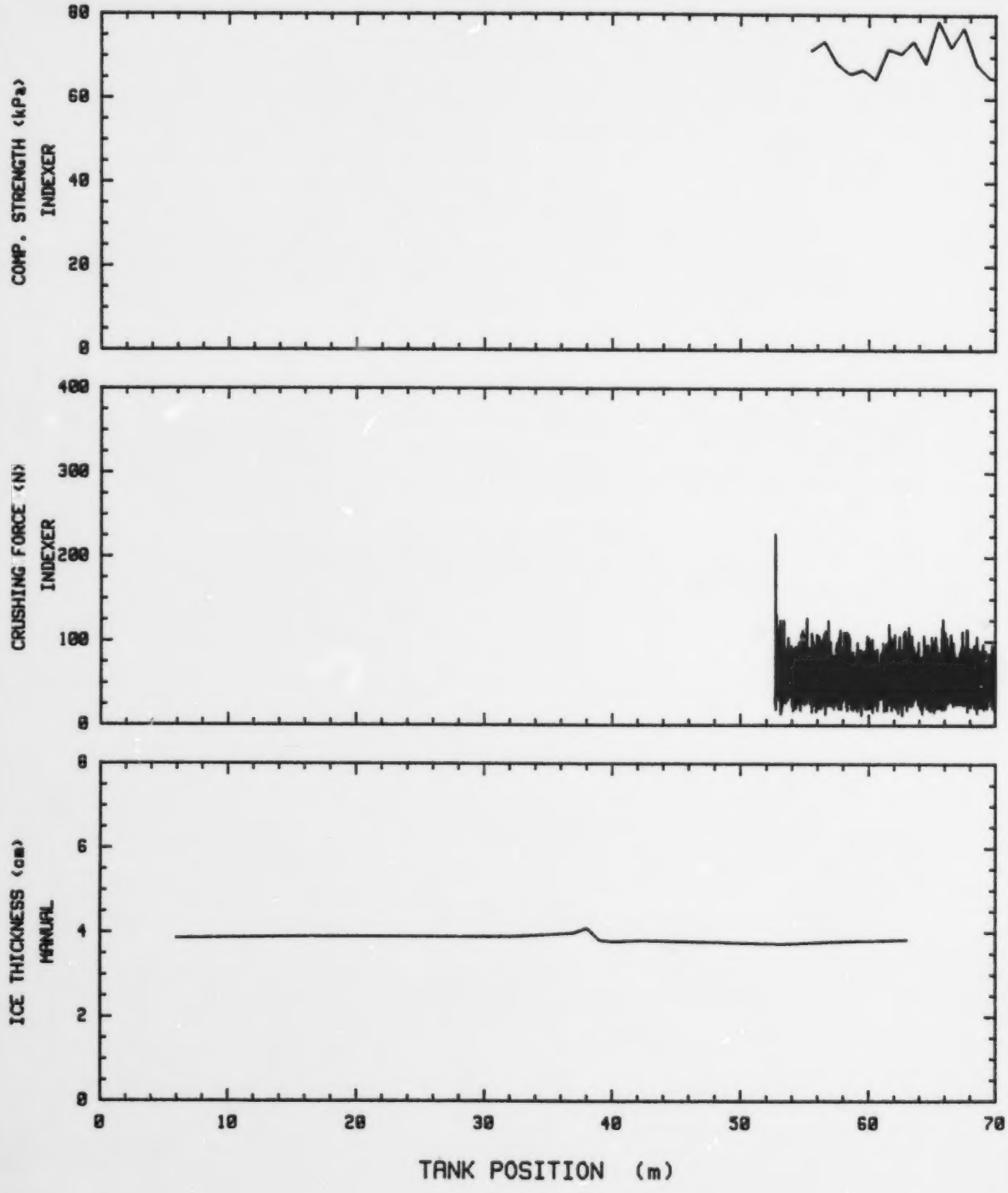


MELVILLE SHIPPING LTD

FIGURE A 2.39

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 4-AUG-1987 14:36:04

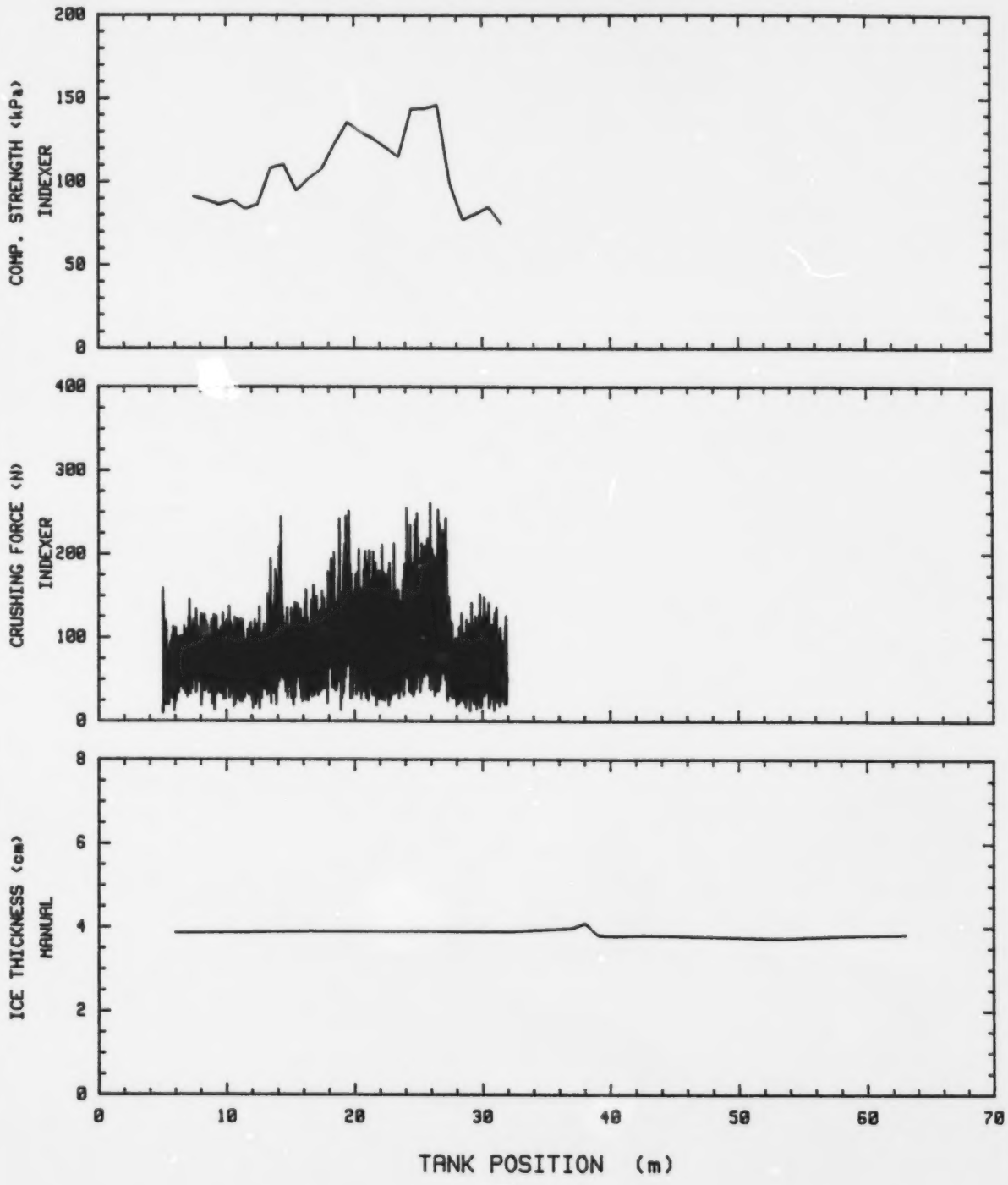


MELVILLE SHIPPING LTD

FIGURE A.2.20

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 4-AUG-1987 16:00:53

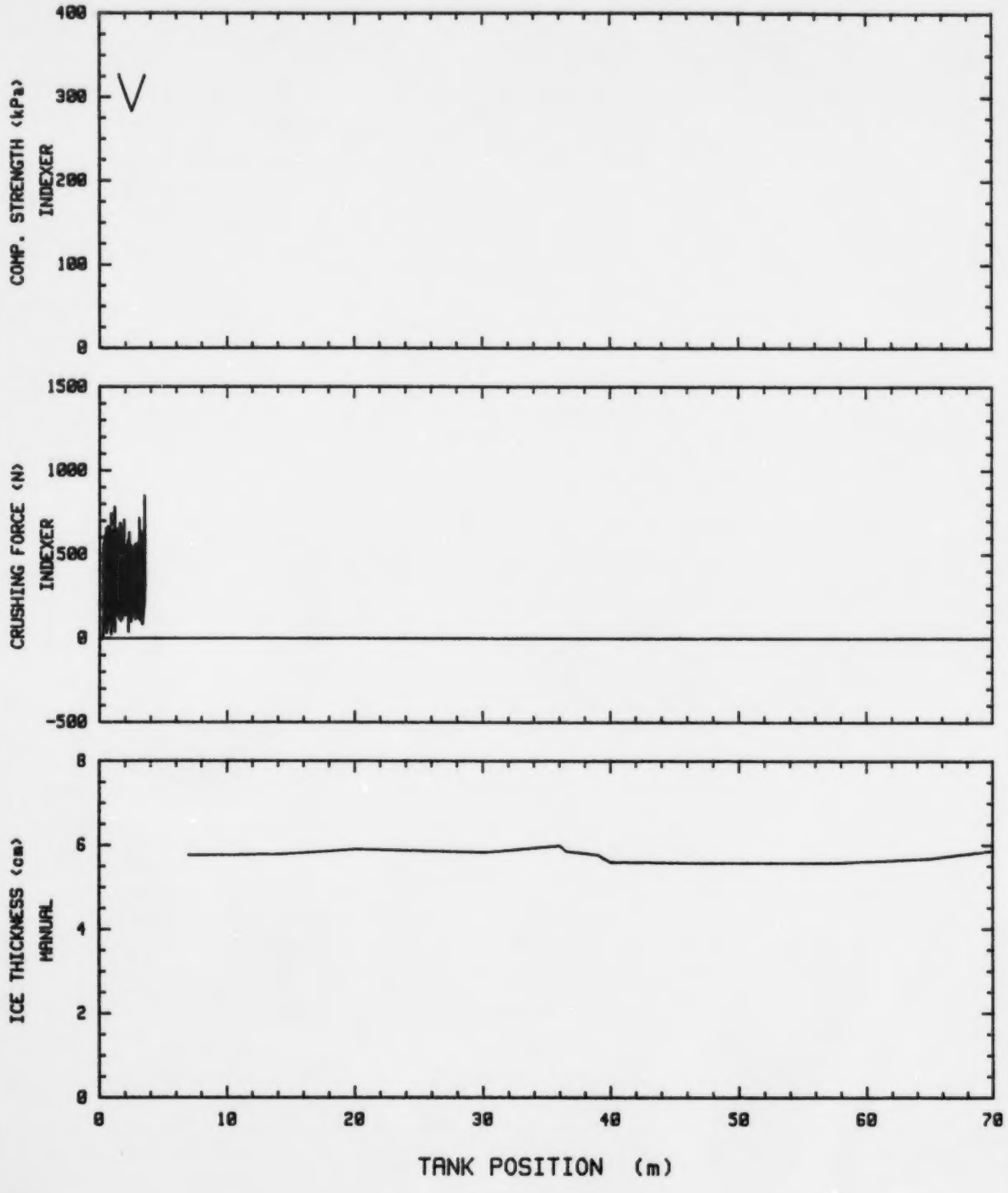


MELVILLE SHIPPING LTD

FIGURE A 2.4

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 7-AUG-1987 13:35:29

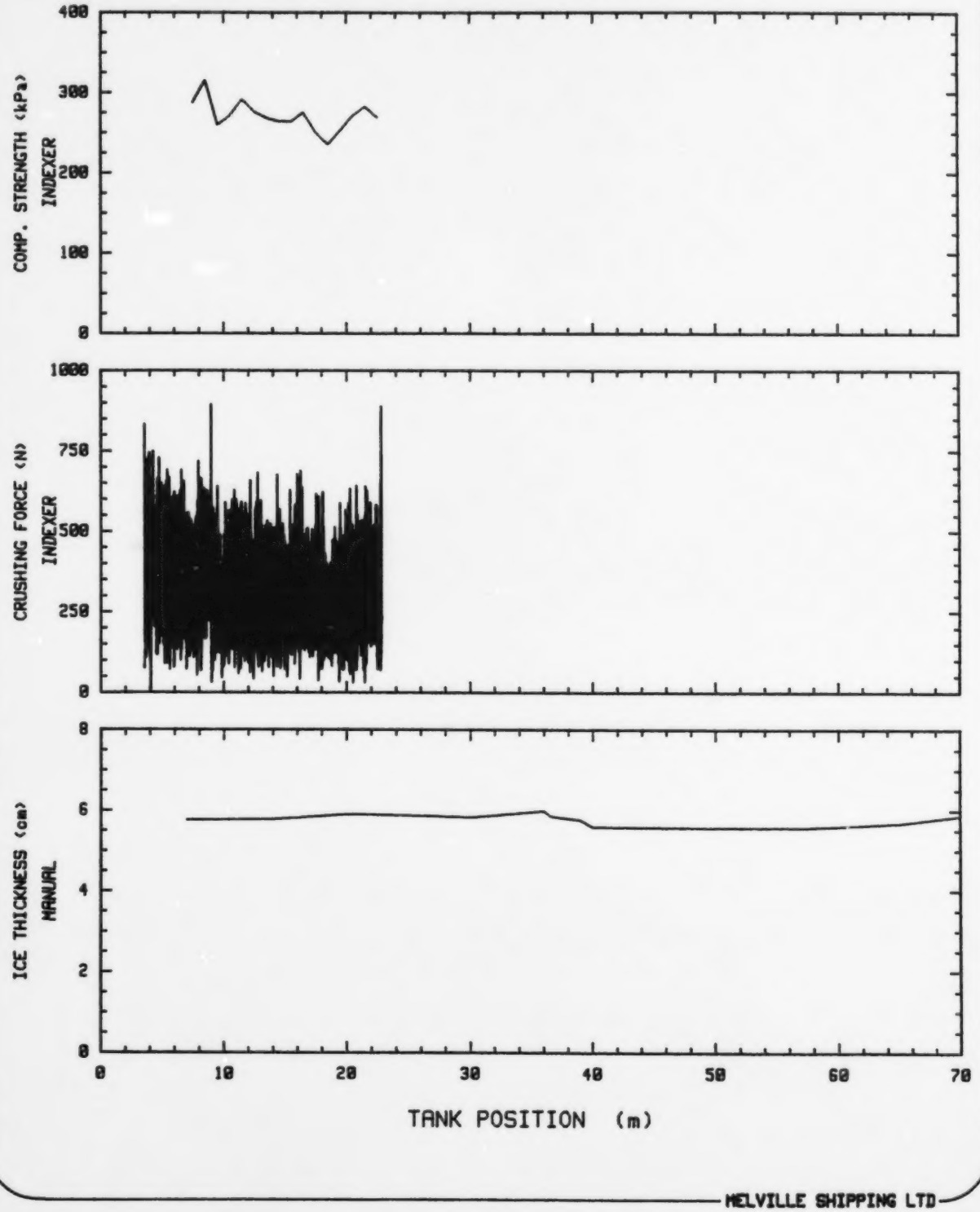


MELVILLE SHIPPING LTD

FIGURE A2.42

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 7-AUG-1987 13:45:49

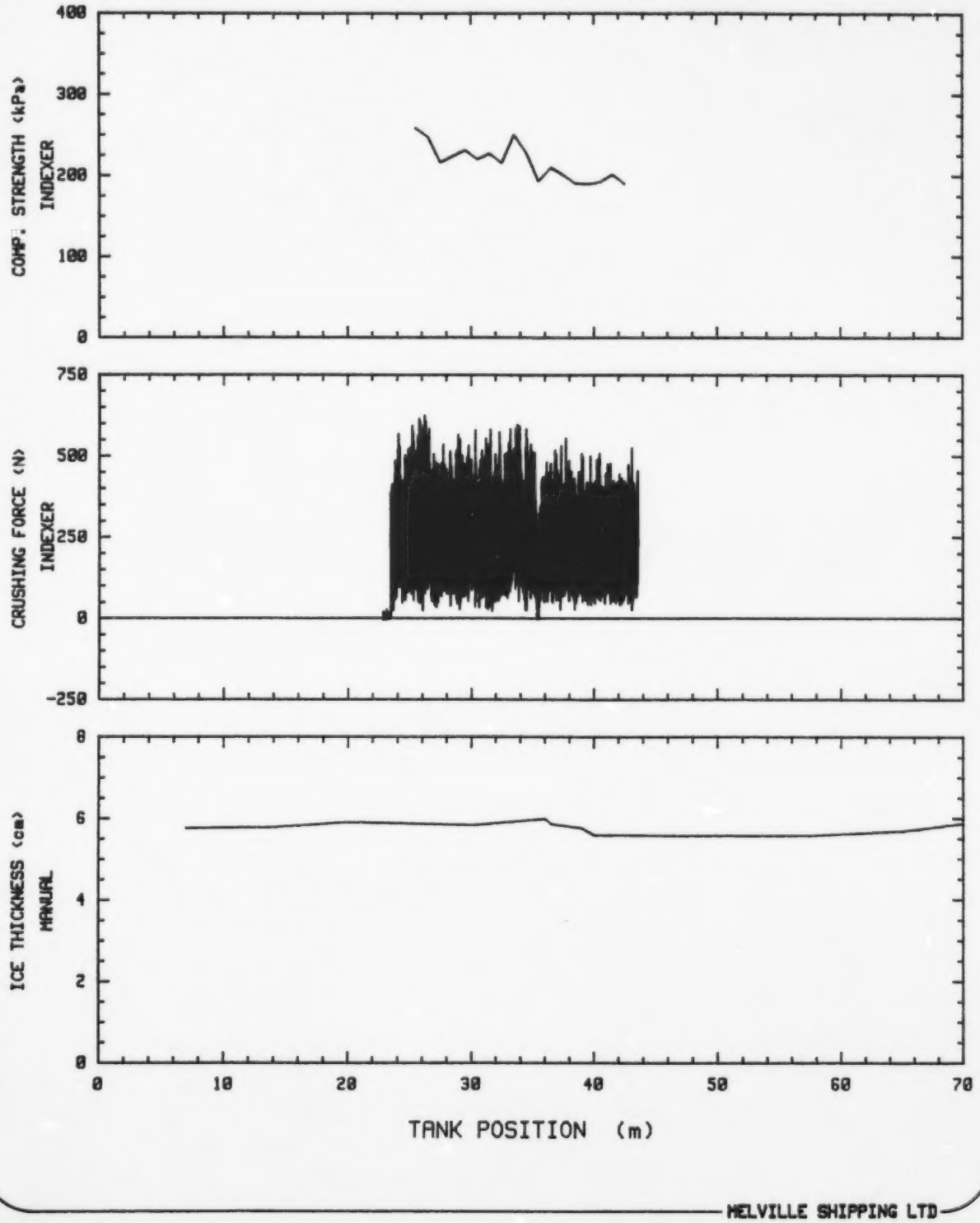


MELVILLE SHIPPING LTD

FIGURE A 2.43

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 7-AUG-1987 15:42:47

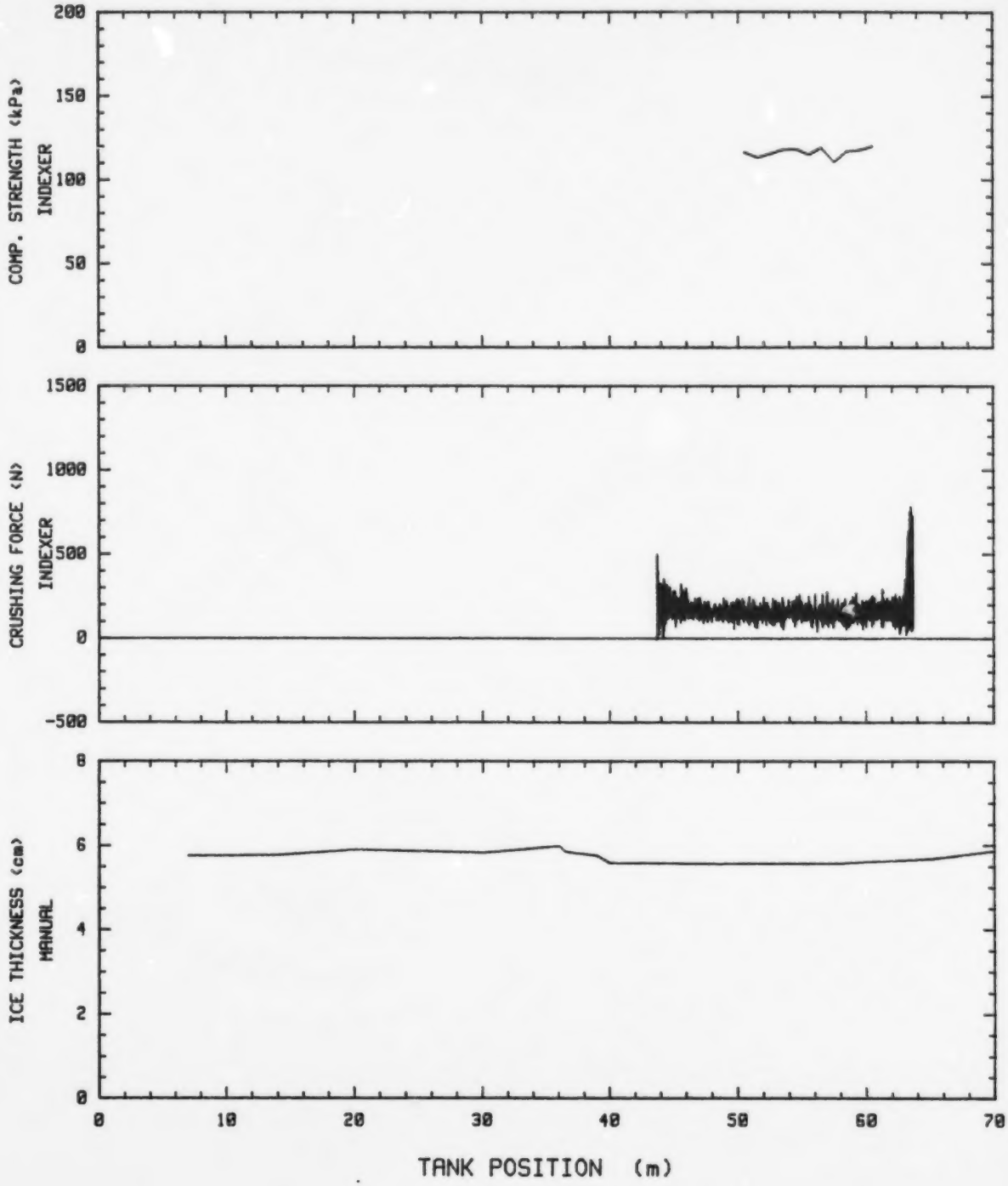


MELVILLE SHIPPING LTD

FIGURE A 2.44

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 7-AUG-1987 16:34:48

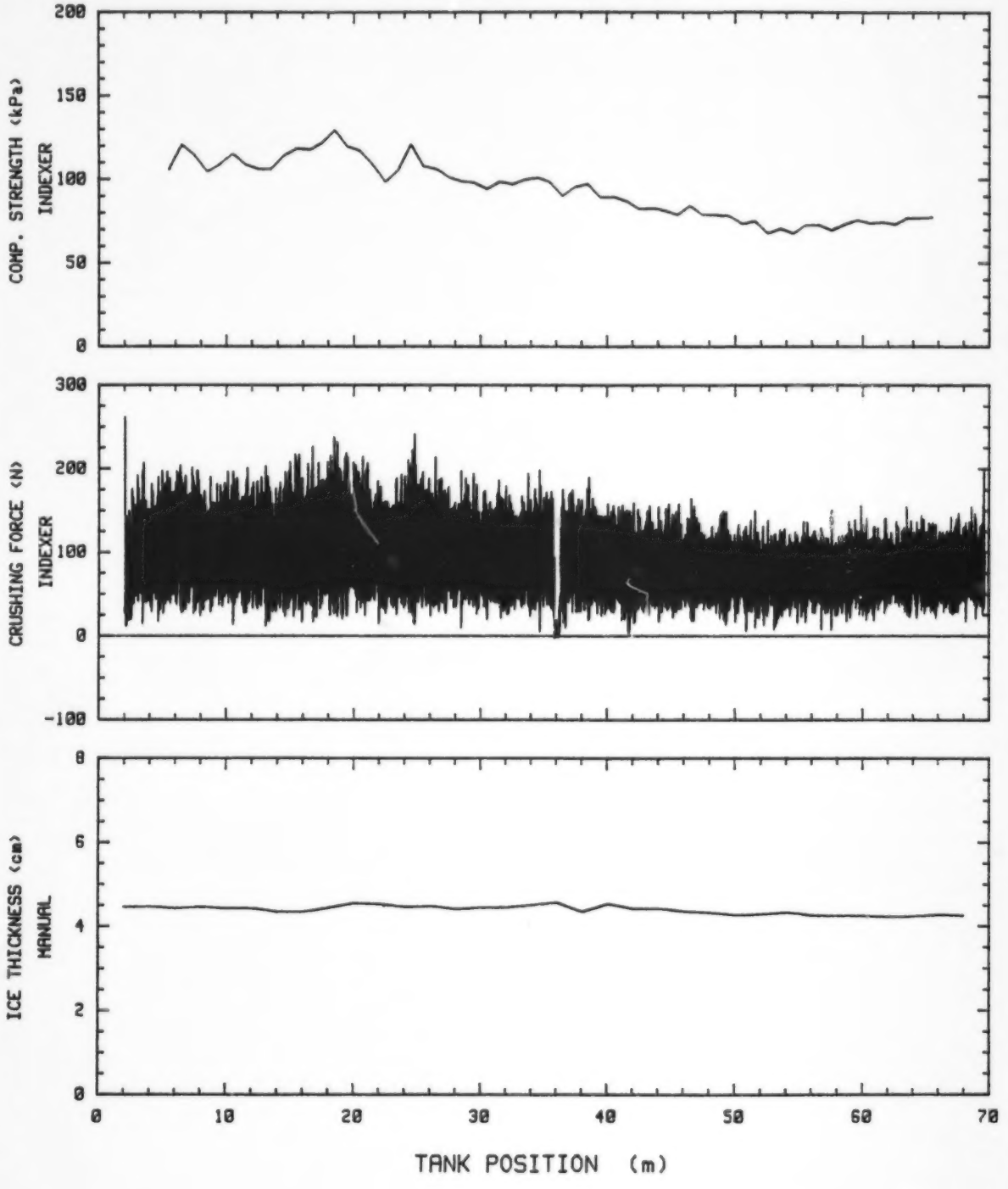


MELVILLE SHIPPING LTD

FIGURE A2.45

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 15-SEP-1987 12:33:15

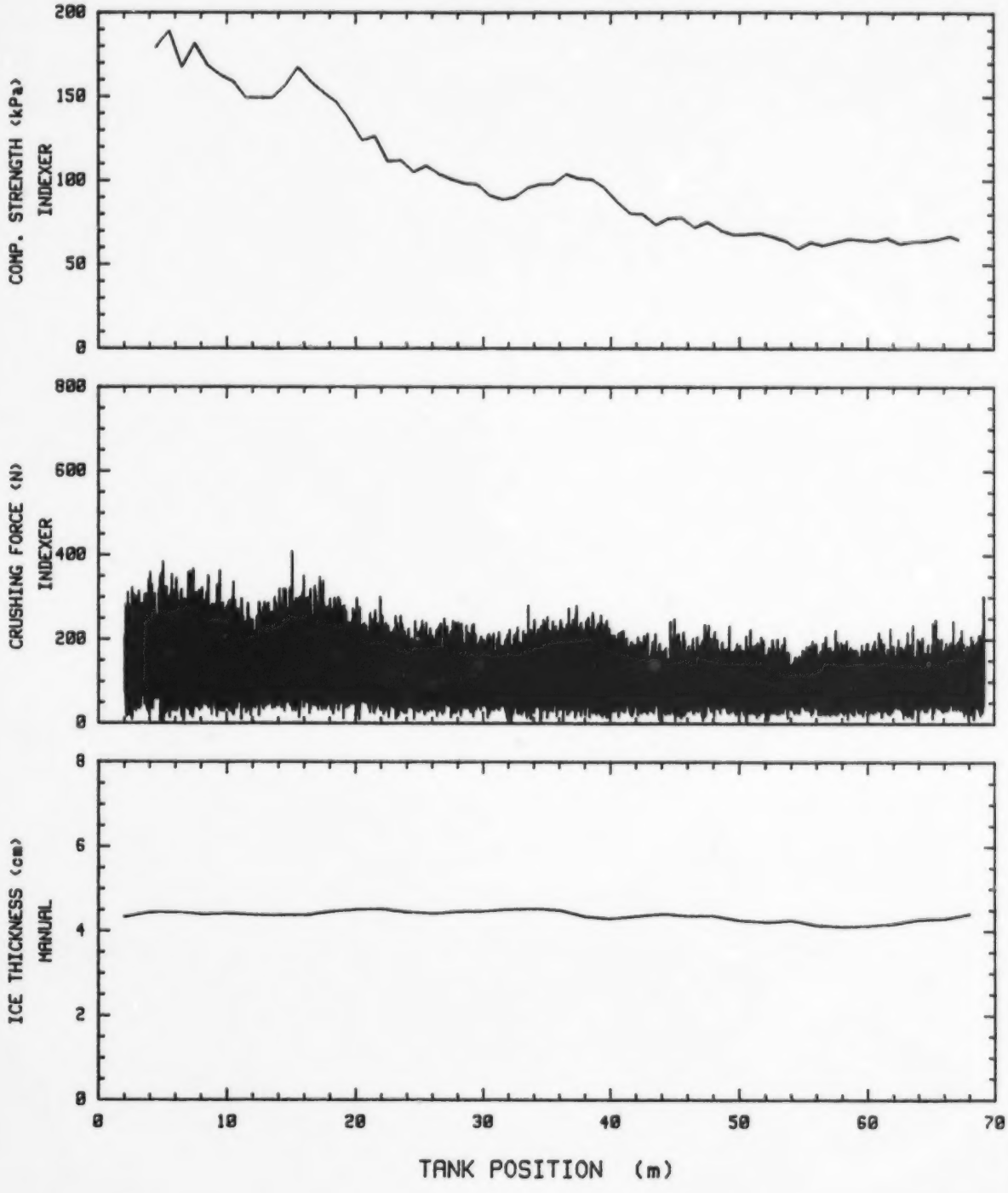


MELVILLE SHIPPING LTD

FIGURE A 2.26

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 16-SEP-1987 17:04:34



MELVILLE SHIPPING LTD

FIGURE A2.47

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 17-SEP-1987 13:18:06

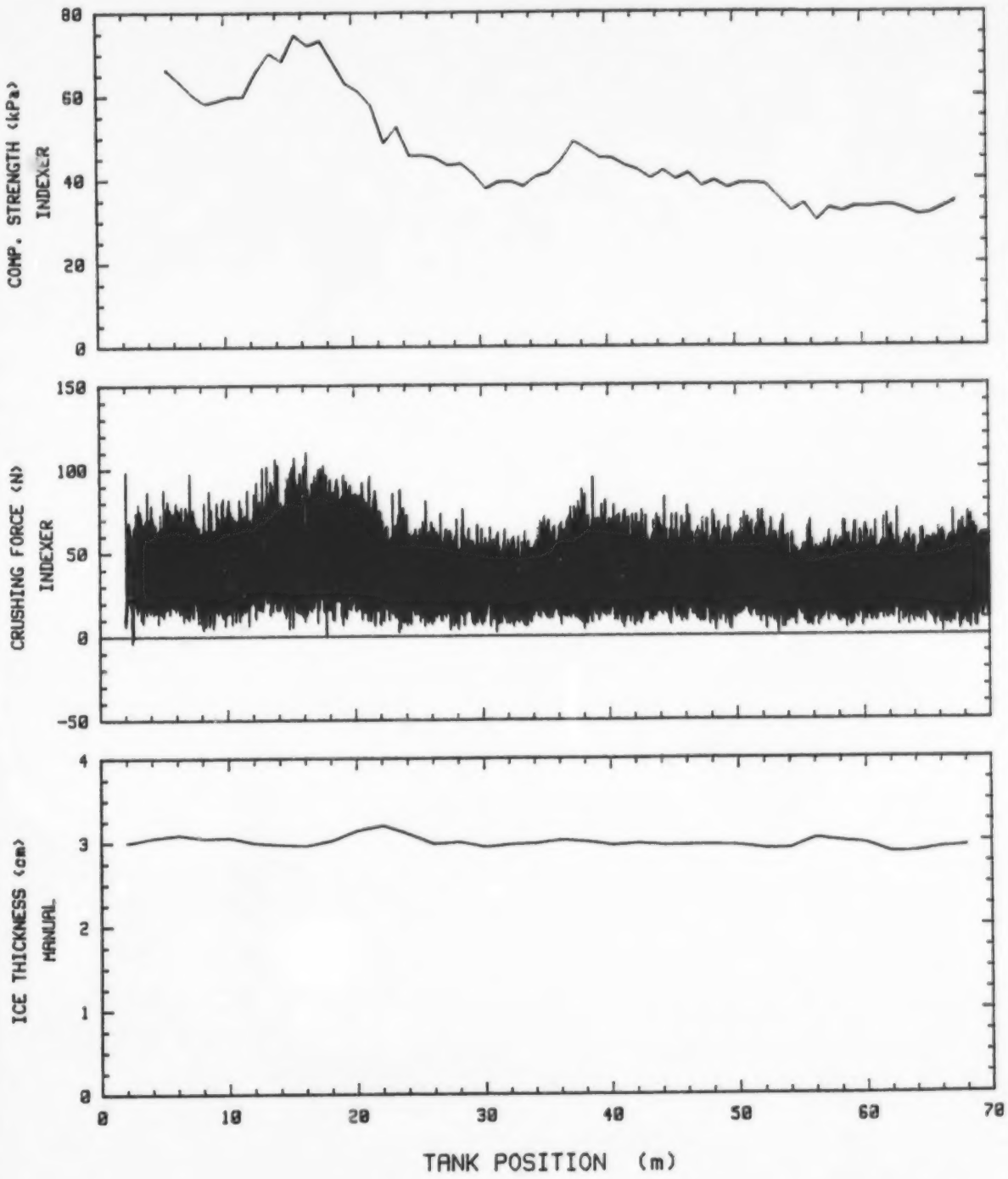


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FIGURE A 2 -3

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 22-SEP-1987 12:00:19

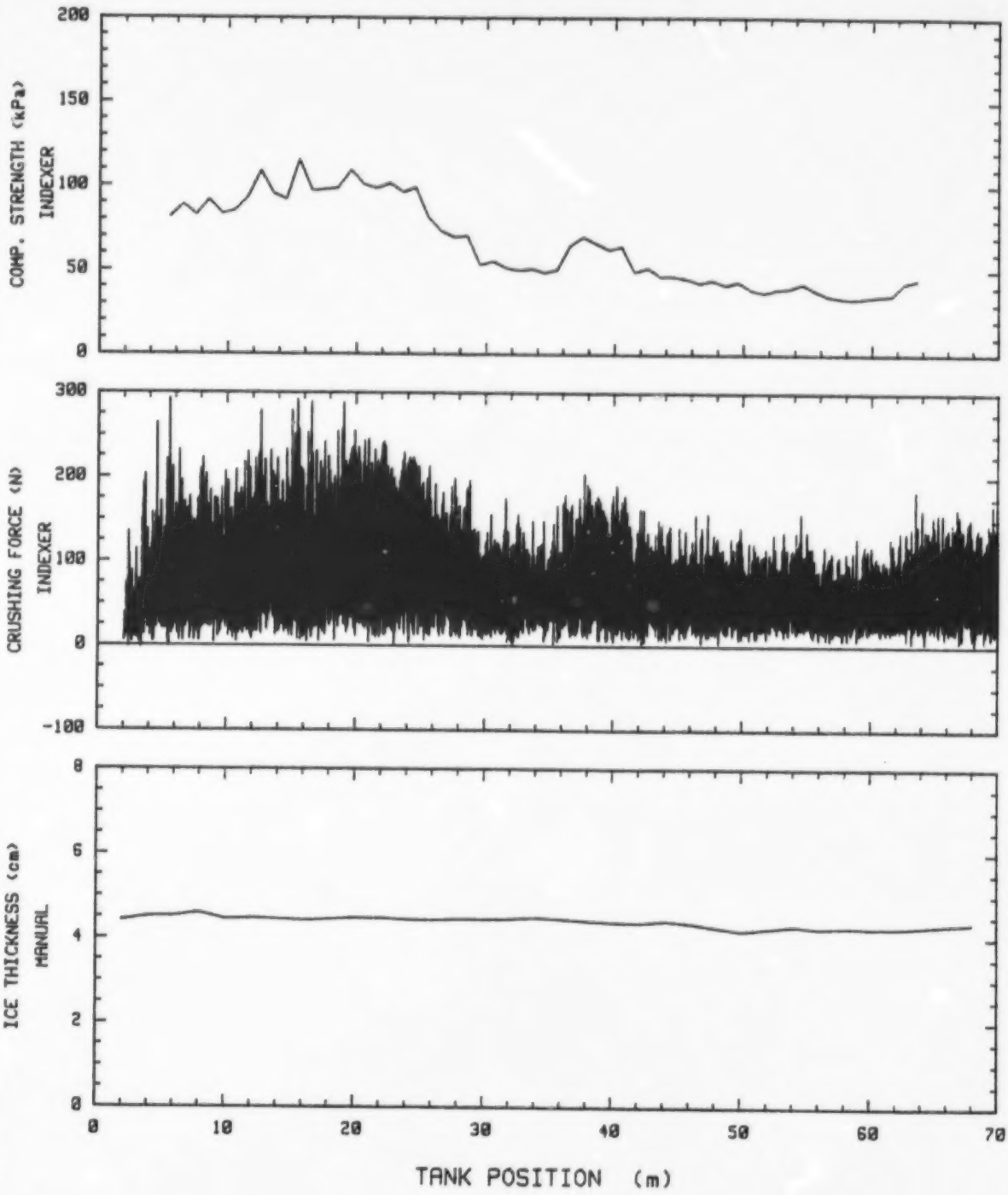

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FIGURE A.2.3

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 24-SEP-1987 15:16:46

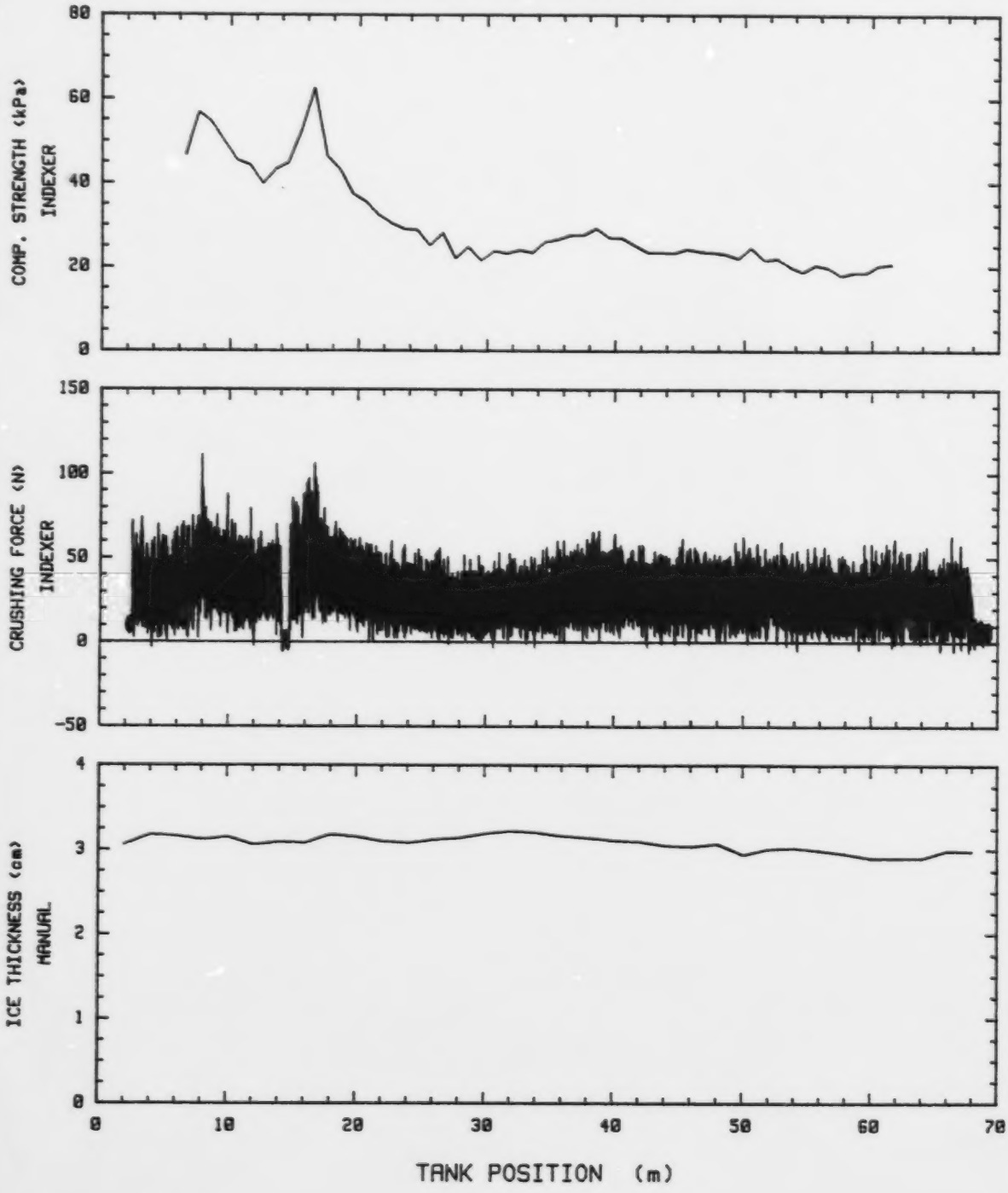

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FIGURE A 2.50

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 6-OCT-1987 18:03:03

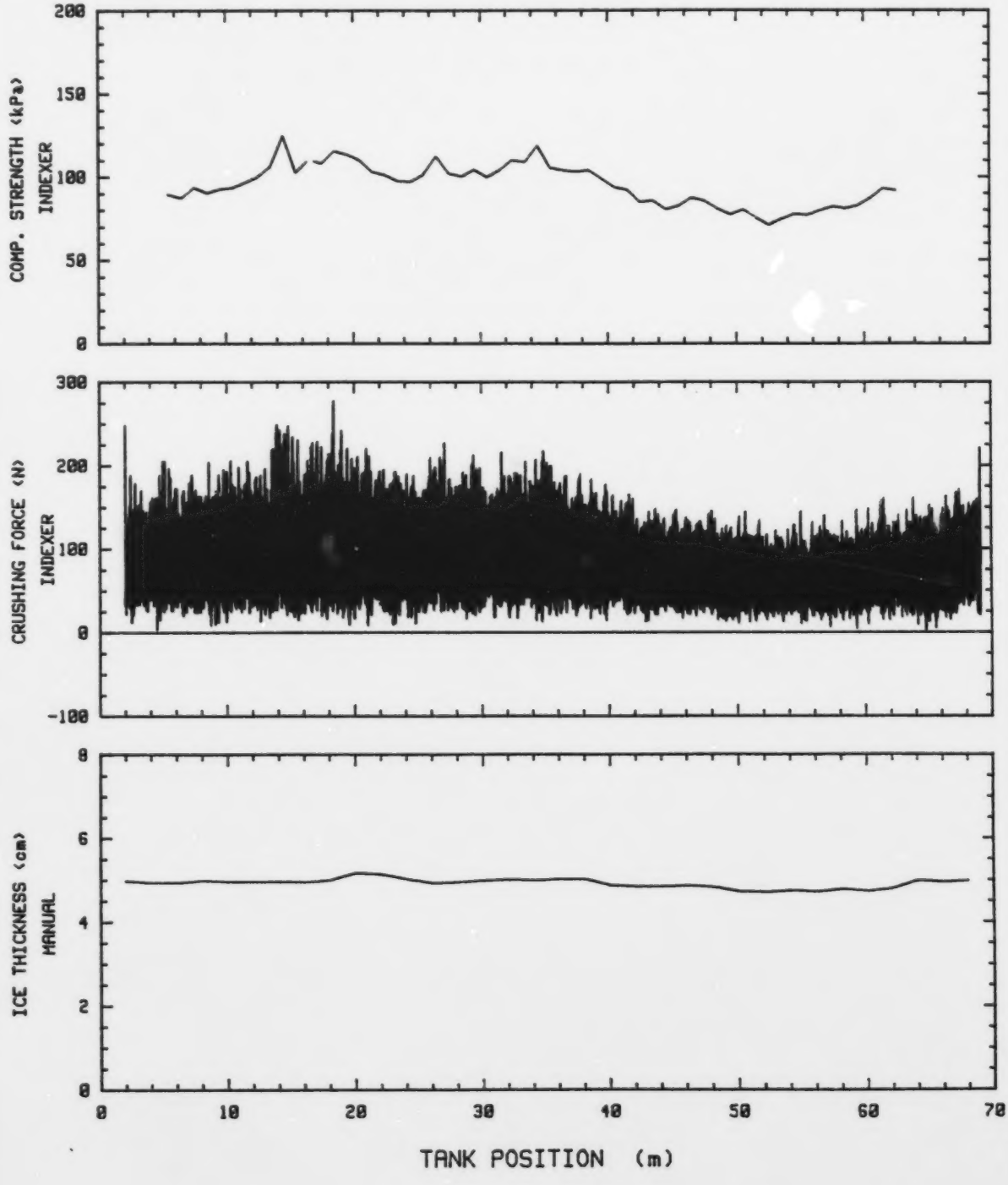

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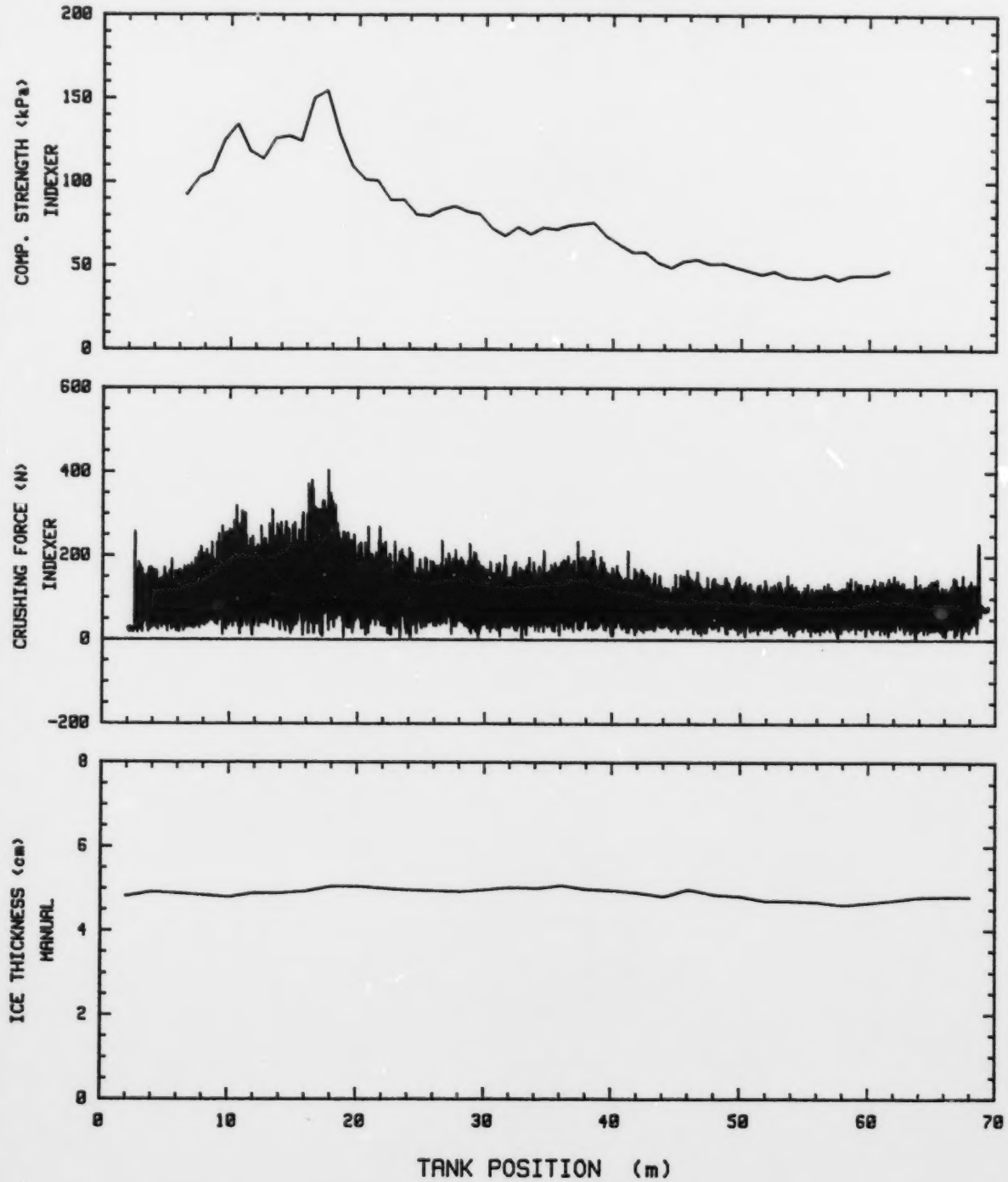
FIGURE A 2.51

ICE SHEET DATA - COMPRESSIVE STRENGTH

RUN 8-OCT-1987 16:59:26



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APPENDIX 3

DESCRIPTION OF COMPUTER PROGRAMME "ICESIM"

A3.1 General

A computer programme (Icesim) has been developed for the analysis of the ice strength and hull form factors. The programme has been developed with the use of a HP-9816 Micro-Computer and is written to simulate the icebreaking process of a given bow as a function of the bow's penetration into ice. The mechanisms of ice crushing, shearing and bending are simulated and, from the simulation results, the relative extent of the breaking component of ice resistance is determined.

The programme code has been developed to perform the following:

Major Functions:

- data input
- bow geometry definition
- ice geometry definition
- icebreaking simulation
- ice force computation
- ice cusps simulation
- force calculation
- calculation of hull form coefficients
- graphics
- data output

A flow chart outlining the overall structure of the computer programme is shown in Figure A3.1. The following text presents an overview of the programme's input requirements, calculation methods, and output formats.

A3.2 Input

A3.2.1 Bow Form

For each run, the programme requires a set of input data to define the bow form and the level ice characteristics. The input bow geometry data includes:

- forebody offsets
- waterline and flare angles

The offsets and hull form angles are required at the waterline for various sections from stem to the forward maximum breadth of the ship. Presently, the programme contains three selected bow forms for testing, namely, the R-Class bow, the M.V. ARCTIC's old and present (Melville) bow designs.

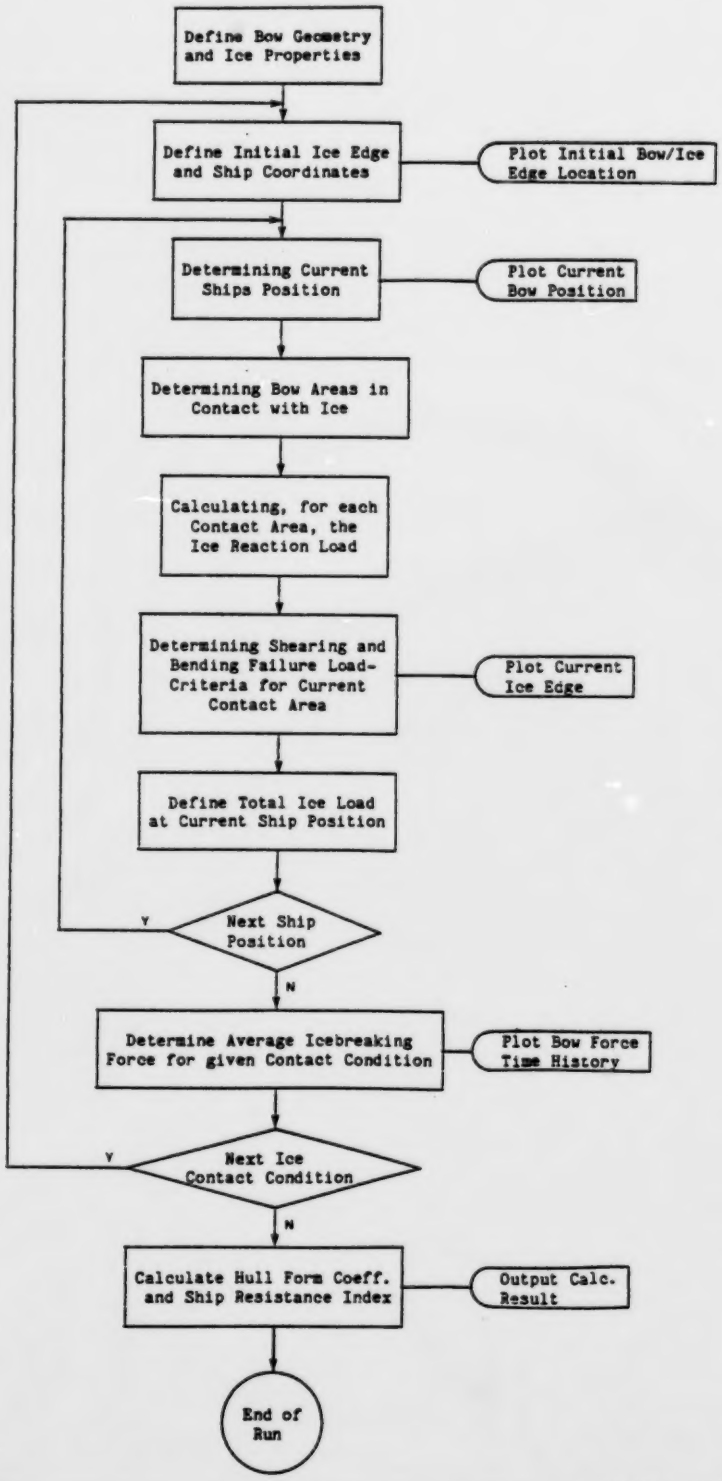
A3.2.2 Ice Characteristics

The ice definition includes:

- thickness
- compressive strength

FIGURE A3.1

"ICESIM" PROGRAMME FLOW CHART


Define Bow Geometry and Ice Properties
Define Initial Ice Edge and Ship Coordinates
Plot Initial Bow/Ice Edge Location
Determining Current Ships Position
Plot Current Bow Position
Determining Bow Areas in Contact with Ice
Calculating, for each Contact Area, the Ice Reaction Load
Determining Shearing and Bending Failure Load-Criteria for Current Contact Area
Plot Current Ice Edge
Define Total Ice Load at Current Ship Position
Next Ship Position
Y
N
Determine Average Icebreaking Force for given Contact Condition
Plot Bow Force Time History
Next Ice Contact Condition
Y
N
Calculate Hull Form Coeff. and Ship Resistance Index
Output Calc. Result
End of Run

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- shear strength
- flexural strength
- elastic modulus
- cusp size

The ice parameters are used for simulating the icebreaking process of the bow, as a result the compressive strength should represent the average condition for loads applied onto the ice from an inclined surface. Similarly, the shear and flexural strengths should represent the condition under a vertical downward load. The elastic modulus is used for determining the characteristic length of the ice. The average width of the ice cusps broken by the bow is defined, from input, as a fraction of the corresponding ice characteristic length.

A3.2.3 Coordinate System

Two sets of coordinate systems are used in the programme: a stationary coordinate system to describe the ship motion, the ice edge and crack conditions, and; a ship coordinate system to define the bow geometry relative to the stem of the ship.

The programme assumes that the average ice force exerted on a ship is symmetrical with respect to the ship's centerline, and therefore only the half-breadth of the bow is defined in the simulation. The bow waterline and ice edge are represented by a set of discrete points, as illustrated in Figure A3.2. The number of points used for the bow and ice geometry definition is flexible and can be selected according to the type of bow and sensitivity of the simulation process. Although th ice and bow coordinates are two dimensional, the vertical deflection of the ice under the action of the bow is considered at each contact point.

The programme features a 'live' graphics capability which allows instantaneous display of the bow position, ice edge and crack conditions during the icebreaking simulation.

A3.3 Calculation Method

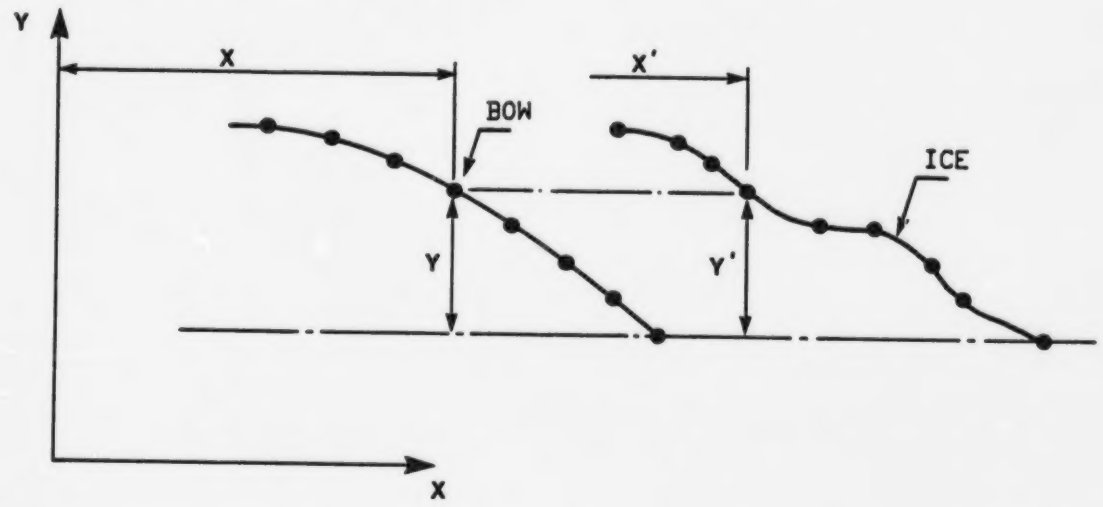
A3.3.1 Simulation

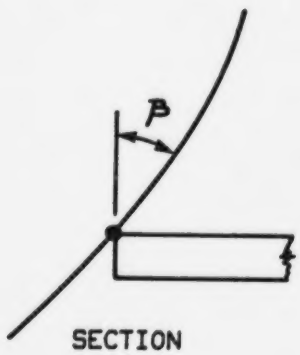
The icebreaking process of a given bow form is simulated as a function of the bow's penetration distance in the ice. The bow is considered to be rigid and moves only in the forward direction. The ship speed, pitching, heaving and other motions are not considered. The simulation is driven by small constant increments of the ship's advance distance.

To assess the average ice force condition at the bow, ten different ship/ice contact conditions are simulated. For each condition, the ice is considered to be semi-infinite and the inital contact with the bow is at the positions shown in Figure A3.3, ranging from stem to shoulder. The simulation is run for each of these starting conditions as the ship penetrates into the ice, the crushing and deflection of the ice is calculated at each increment of the ship position, and the resultant

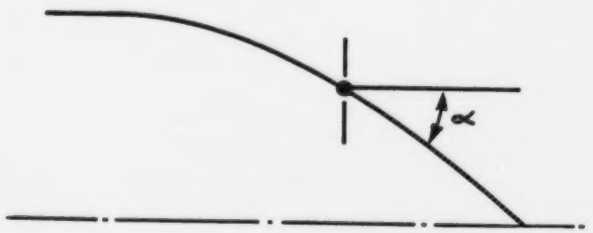
FIGURE A3.2

COORDINATE SYSTEM





SECTION



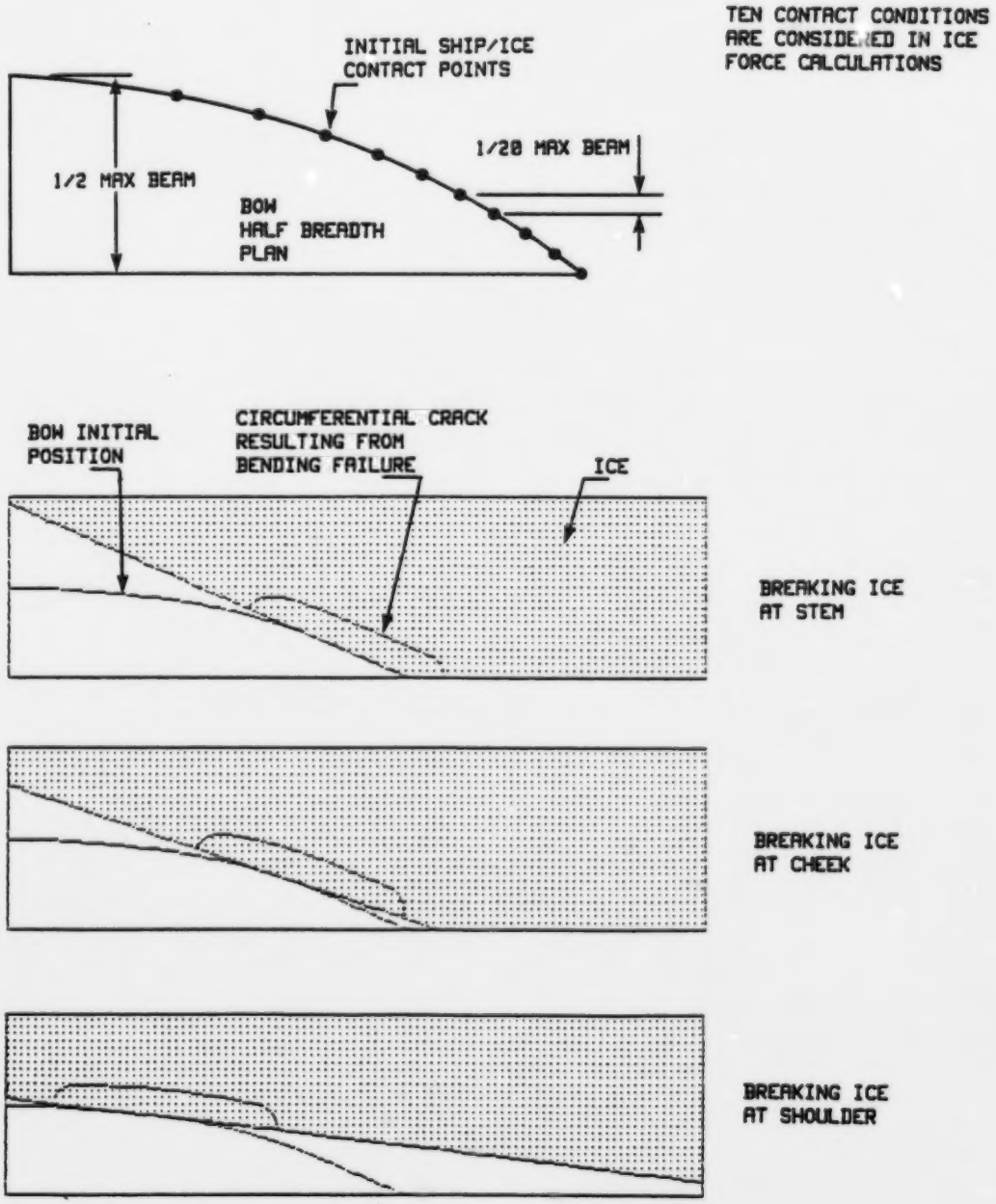
PLAN

BOW	ICE
X, Y COORDINATES FLARE ANGLE WATERLINE ANGLE	X, Y COORDINATES

NOTE :
ORDINATES AND FLARE AND WATERLINE ANGLES DEFINED FOR A WATERLINE AT THE MIDDLE OF THE ICE THICKNESS

FIGURE A3.3

ASSUMPTION OF ICE GEOMETRY
AND CONTACT CONDITIONS


TEN CONTACT CONDITIONS ARE CONSIDERED IN ICE FORCE CALCULATIONS
INITIAL SHIP/ICE CONTACT POINTS
1/20 MAX BEAM
1/2 MAX BEAM
BOW HALF BREADTH PLAN
BOW INITIAL POSITION
CIRCUMFERENTIAL CRACK RESULTING FROM BENDING FAILURE
ICE
BREAKING ICE AT STEM
BREAKING ICE AT CHEEK
BREAKING ICE AT SHOULDER

shearing and/or bending failure of the ice is examined at each increment. The ship ice contact area, and direction, are quantified for each ship position based on the bow waterline and ice edge coordinates. The ice forces are deduced from the contact conditions. An new ice edge is defined whenever a shear or bending failure is created. The simulation is restarted at the next contact point after the ice fails in bending and the resultant broken ice cusp has been simulated. The simulation, from initial contact to the formation of an ice cusp, is carried out for each of the preselected ice contact conditions. The accumulated ice forces during the simulation are then used to calculate the hull form coefficients and the relative ice breaking component of the bow's resistance.

A3.3.2 Ice Force Calculation

The ice force exerted on the bow is calculated from the contact area and deflection condition of the ice. The contact area is subdivided into a set of elements as shown in Figure A3.4, and the force vector is determined from each element and these summed to obtain the resultant forces.

The ice is assumed to be crushed continuously by the bow, at the contact area, and the force to be normal to the contact surface and proportional to the nominal ice compressive strength. Forces due to friction between the ice and the bow are not presently included in the programme. The vertical deflection of the ice is approximated by the relationship developed by Nevel (1965) and Naegle (1980) for a simple ice loading geometry. The equations which are used in the computer programme for ice force and deflection calculations are as follows:

$$F_N = \sigma_c \cdot b \cdot H_c / \sin\beta'$$

$$F_z = F_N \sin\beta'$$

$$F_x = F_N \cos\beta' \sin\alpha$$

$$F_y = F_N \cos\beta' \cos\alpha$$

$$\beta' = \tan^{-1}[\tan\beta \cos\alpha]$$

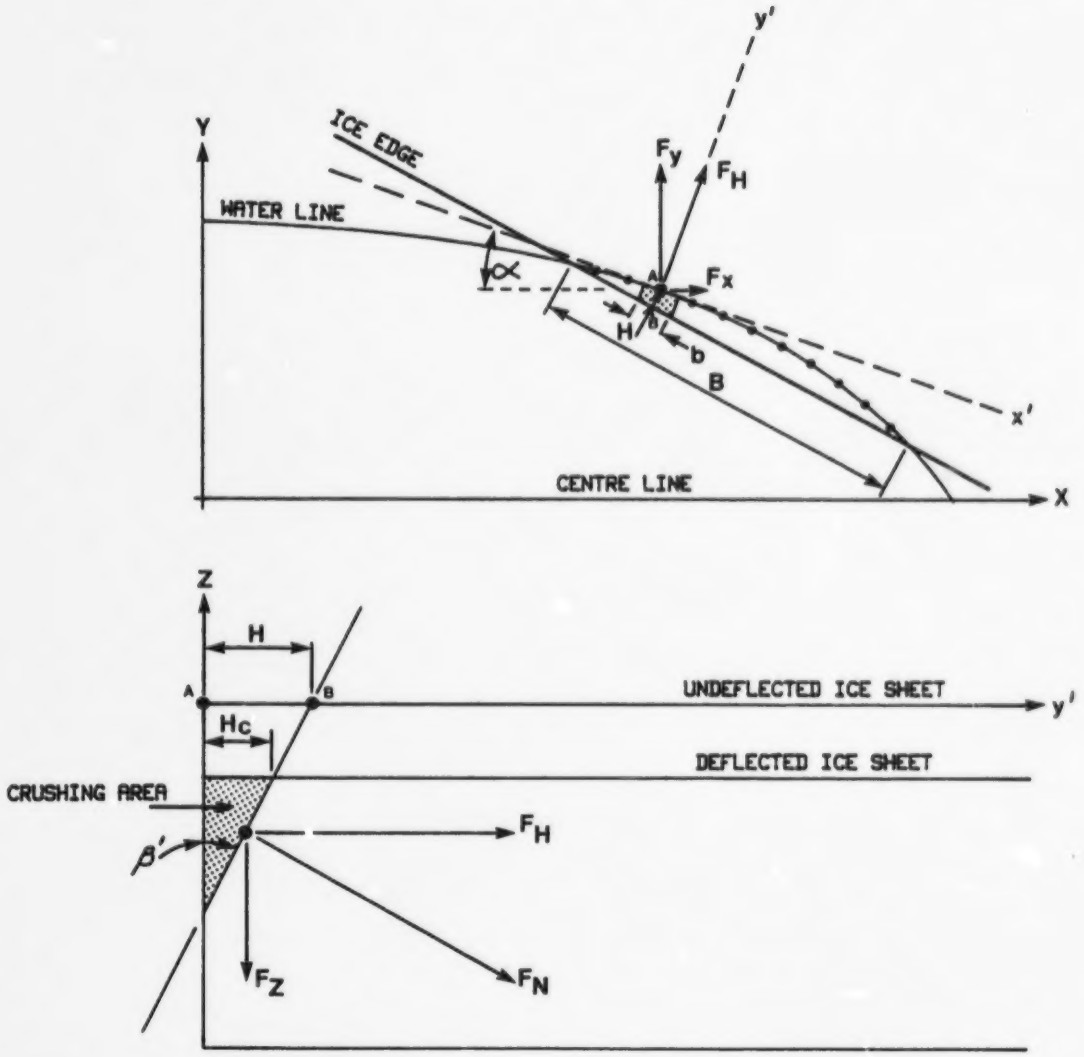
$$H_c = H\left[1 + 0.4697 \frac{\sigma_c \cdot B}{\rho g \ell_c^2} \tan\beta' \cdot e^{-0.4396 \frac{B}{\ell_c}}\right]^{-1}$$

$$\ell_c = \left[E h^3 / (12 \rho g (1-\nu^2))\right]^{0.25}$$

where
- F_N = ice force at contact point
- F_x, F_y, F_z = x, y, z components of F
- σ_c = ice compressive strength
- α = waterline angles at contact point
- β = frame flare angle at contact point
- H_c = crushing distance in the direction perpendicular to hull surface at contact point
- H = ship penetration distance in the direction perpendicular to hull surface at contact point
- h = ice thickness
- ℓ_c = ice characteristic length
- B = total width of contact area
- b = width of contact area element
- ρ = water mass density
- ν = poisson ratio

FIGURE A3.4

CALCULATION OF ICE FORCE



The total vertical component of the ice force, developed at the contact area, is compared with the limit loads for shearing and bending failure. The shearing failure load limit is assessed by considering a vertical shear surface across the thickness of the ice, at the contact area.

$$P_s = \sigma_s \cdot h \cdot B$$

where P_s = shear load limit
σ_s = ice shear strength

The bending load limit is assessed by considering an equation used by Carter (1983) and is used in the programme to determine the vertical force limit. The limit load is augmented by a consideration of any horizontal compressive stress in the ice due to bow forces. This is accomplished using an approximation method as illustrated in the following equations.

$$P_f = 0.5482 \left[\frac{\pi}{2} + \frac{B}{\ell_c}\right]\left[\sigma_f + \Delta\sigma_f\right] h^2$$

$$\Delta\sigma_f = \frac{F_N \cdot \cos\beta'}{b \cdot h}$$

where P_f = bending load limit
σ_f = ice flexural strength

A3.3.3 Ice Cusping

Figure A3.3 illustrates the shape of the ice cusp simulated by the computer programme after bending failure occurs. The circumferential crack is defined by assuming a constant cusp width from the ship/ice contact point to the crack. The cusp width has been assumed to be proportional to the ice characteristic length which is a function of the ice thickness and elasticity.

A3.3.4 Resistance Calculation

After each simulation, the relative resisting force to the ship's motion due to icebreaking is assessed from the energy required and the effective icebreaking area involved during the simulation period. The icebreaking energy calculated includes the work associated with the deflection of the ice and the longitudinal motion of the ship when it is crushing ice. The effective icebreaking area considers all the area of the originally unbroken level ice being crushed, sheared and broken by the bow. Broken ice beyond the maximum beam of the ship is not considered since it does not affect the resistance of the ship.

The final resistance force is computed by averaging the simulation results obtained from the different contact positions;

$$R = \frac{B}{N} \sum_{i=1}^{N} \frac{E_i}{A_i}$$

where R = average icebreaking resistance
E_i = icebreaking energy required
A_i = effective icebreaking area
B = ship's beam
N = no. of simulation conditions (10)

A3.3.5 Hull Form Coefficients

The programme computes three hull form coefficients to depict the icebreaking effectiveness of a particular bow. These coefficients are:

- crushing coefficient
- shear coefficient
- bending coefficient

The crushing coefficient is defined as the ratio of the volume of the crushed ice to the total volume of the ice being broken by the ship, the shearing coefficient is defined as the ratio of the ice removed by shearing to the total ice volume, and the bending coefficient is defined as the ratio of the ice volume removed by bending failure to the total ice volume. The sum of the three coefficients is always equal to unity.

A3.4 Output

Figure A3.5 shows the output from a typical run of the simulation programme which contains:

- the bow indentification and ice conditions selected for the simulation run,
- a summary of the results from each of the ten simulation conditions inlcuding the maximum forces, energy, icebreaking area, and the derived relative icebreaking resistance.
- hull form coefficients and icebreaking resistance averaged from the calculations.

In addition, a graphical display of the ship waterline, the current ship position and ice edge conditions is provided during the simulation on the computer's CRT monitor.

FIGURE A3.5

SAMPLE OUTPUT OF "ICESIM"

ICEBREAKING SIMULATION
RUN_1

BOW: M.V. ARCTIC (MELVILLE BOW)

ICE THICKNESS (m):	.03333
CRUSHING STRENGTH (Pa):	50001
FLEXURAL STRENGTH (Pa):	16667
SHEAR STRENGTH (Pa):	33334
ELASTIC MODULUS/FLEXURAL STRENGTH:	2000
ELASTIC MODULUS (Pa):	3.3334E+7
ICE CHARACTERISTIC LENGTH (m):	.329661
CUSP WIDTH/ CHAR. LENGTH :	.3
SHIP SCALE FACTOR (LAMDA):	30

CONTACT LOC (Y/.5B)	MAX Fx (N)	MAX Fy (N)	MAX Fz (N)	ENERGY SPENT (W)	AREA (m2)	RESISTANCE (N)
0.0	10.9	22.3	35.8	.353	.075	3.601
.1	10.9	22.4	36.4	.341	.077	3.367
.2	10.9	22.2	35.8	.350	.075	3.563
.3	10.8	22.2	35.7	.340	.075	3.460
.4	10.9	22.7	37.0	.338	.079	3.238
.5	10.6	22.9	38.3	.332	.084	3.000
.6	8.5	21.6	36.0	.384	.075	3.893
.7	7.1	22.9	33.9	.365	.062	4.488
.8	6.9	31.8	34.8	.404	.051	6.038
.9	11.2	87.9	42.8	.702	.032	16.623

HULL FORM COEFFICIENTS- CRUSHING: .021284
SHEARING: 0
BENDING: .97872

AVERAGE ICEBREAKING RESISTANCE(N): 5.1209